Fuel Economy Modeling of Light-Duty and Heavy-Duty Vehicles, and Coastdown Study

by

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Fuel Economy Modeling of Light-Duty and Heavy-Duty Vehicles, and Coastdown Study

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Dedication

To my mother Zeynep Ates, who put a lot of effort on me and dedicated her life for mine getting well education and being a responsible human for the world and for my family, to my father Abdullah Ates, who instilled in me the desire to learn and be perfect in my life and having high standards and to my sister Zeliha Ates, who is next to me whenever I need support in my life.

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Abstract

Fuel Economy Modeling of Light-Duty and Heavy-Duty Vehicles, and Coastdown Study

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The University of Texas at Austin, 2009

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Development of a fuel economy model for light-duty and heavy-duty vehicles is part of the Texas Department of Transportation's "Estimating Texas Motor Vehicle Operating Costs" project. A literature review for models that could be used to predict the fuel economy of light-duty and heavy-duty vehicles resulted in selection of coastdown coefficients to simulate the combined effects of aerodynamic drag and tire rolling resistance.

For light-duty vehicles, advantage can be taken of the modeling data provided by the United States Environmental Protection Agency (EPA) for adjusting chassis dynamometers to allow accurate determination of emissions and fuel economy so that compliance with emissions standards and Corporate Average Fuel Economy (CAFE) regulations can be assessed. Initially, EPA provided vehicle-specific data that were

relevant to a physics-based model of the forces at the tire-road interface. Due to some limitations of these model parameters, EPA now provides three vehicle-specific coefficients obtained from vehicle coastdown data. These coefficients can be related back to the original physics-based model of the forces at the tire-road interface, but not in a manner that allows the original modeling parameters to be extracted from the coastdown coefficients. Nevertheless, as long as the operation of a light-duty vehicle does not involve extreme acceleration or deceleration transients, the coefficients available from the EPA can be used to accurately predict fuel economy.

Manufacturers of heavy-duty vehicles are not required to meet any sort of CAFE standards, and the engines used in heavy-duty vehicles, rather than the vehicles themselves, are tested (using an engine dynamometer) to determine compliance with emissions standards. Therefore, EPA provides no data that could be useful for predicting the fuel economy of heavy-duty vehicles. Therefore, it is necessary to perform heavy-duty coastdown tests in order to predict fuel economy, and use these tests to develop vehicle-specific coefficients for the force at the tire-road interface. Given these coefficients, the fuel economy of a heavy-duty vehicle can be calculated for any driving schedule. The heavy-duty vehicle model developed for this project is limited to pre-2007 calendar year heavy-duty vehicles due to the adverse effects of emissions components that were necessary to comply with emissions standards that went into effect January 2007.

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Chapter 1 Introduction

Why is fuel economy important? In 2008, price of the crude oil went as high as $145 a barrel in New York trading where regular gasoline pump price passed $4 per gallon for the consumer in the US. Few industrial natural sources impact the world economy directly like the oil prices. As oil prices rise, cost of the transportation increases directly where it reflects to other products indirectly and finally it shows its impact on the people's lives as inflation.

Moreover, carbon dioxide emitted from the tailpipes of the vehicles contributes to the global warming. According to EPA, 51% of the CO_2 emissions in a typical household are from vehicles owned in that household.[1] Oil is a non-renewable source and hybrid and electric vehicle technologies have not yet developed extensively to meet customers' needs. Reducing the rate of the oil usage will allow time to scientists to create a better world for our future.

The purpose of this thesis is to develop a computer based fuel economy model to predict the fuel consumption of light-duty and heavy-duty vehicles. Two different modeling approaches analyzed and two different models created for light-duty passenger vehicles. First approach is a generalization of the vehicles to classes and modeling the fuel economy for each class of the light-duty vehicles (LDV's). EPA classifies light-duty vehicles according to their Gross Vehicle Weight Ratings (GVWR) and the cargo volume. A similar classification also exists for the heavy-duty vehicles (HDV's); however the classification is based on the GVWR and the number of axles.

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[1] http://www.fueleconomy.gov/feg/emissions/GHGemissions.htm

Second approach is a vehicle specific modeling of the fuel economy by using the engine performance characteristics with the efficiency models of the engine and the drivetrain. Total resistive forces on the light-duty vehicles can be calculated by the coastdown coefficients released for every light-duty vehicle sold in the US by the EPA. These resistive forces are related with engine power required to move vehicle forward through efficiency models i.e. transmission efficiency, differential efficiency, and other engine efficiency models like mechanical efficiency, indicated thermal efficiency, and combustion efficiency. The engine power produced to move vehicle forward against the resistive forces is extracted from the fuel combusted through a combustion process. The fuel needed to produce engine power required in a specific vehicle ground speed gives the fuel economy that is broadly known as the "mpg" which is the engineering units of the fuel economy in miles per gallon (mpg).

Chapter 2 of this thesis details the basics of the vehicle dynamics, including aerodynamic drag forces, rolling resistance forces, and the forces imposed on the vehicle due to grade. Comparison of the vehicles is of great importance in the automotive industry in each vehicle class regarding fuel consumption. Thus, road load power requirements of the vehicle are analyzed as a standard. Coastdown and chassis dyno tests are discussed, along with the three coastdown coefficients and effective mass term.

Next chapter details the basics of the four-stroke internal combustion engines widely used in the automotive industry. The author analyzes the engine power which is the source to overcome the resistive forces explained in Chapter 2 and an introduction to dynamometers also included to make a fundamental physical approach. In developing the fuel economy model, stoichiometry of the air-fuel mixture is discussed which is necessary to model combustion process accurately. Both of the fuel economy models are directly related with engine efficiencies, thus; in addition to specific engine operating efficiencies like indicated thermal efficiency, combustion efficiency, and mechanical efficiency; an overall engine efficiency is described from point of classical thermodynamics.

Chapter 4 discussed the vehicle class approach of the fuel economy modeling of the LDV's. Vehicle categories and vehicle class requirements are discussed in addition to effects of the 2008 EPA fuel economy calculation method and new window stickers. Mathematical model is analyzed using the physical equations derived in Chapter 2 and the engine efficiency models discussed in Chapter 3. Moreover EPA's fuel economy calculation method is mathematically explained and related with the mathematical expression derived at the beginning of the chapter with the overall drivetrain efficiencies.

Next, vehicle specific fuel economy model is discussed by modeling every parameter of the engine and relating the power output of the engine through the transmission end differential efficiency models to the road load power requirements of the vehicle by using the coastdown coefficients. In developing the engine performance model the Air Equivalent SI Engine Model is discussed in addition to intake, compression, ignition, power, and exhaust strokes of the engine. Moreover, the fuel economy mathematical model bundled to user-friendly software on the Microsoft's .NET platform which uses MATLAB codes in the background for capabilities of the MATLAB. An installation setup is developed with Visual Studio 2008 for easy distribution.

Chapter 6 discussed the SAE Recommended Coastdown Practice J1263 in details starting from the instrument requirements, track specifications and the terms to the procedure that needs to be followed during the coastdown tests. A Vehicle Data Sheet is attached in Appendix D: for completeness of the procedure.

Next, analytical analysis of the coastdown tests are discussed in details. Korst's mathematical approach is mixed with Yasin's approach and at the end equations are altered in our needs for easy calculation of the coastdown coefficients. The criteria explained in the SAE J1263 Coastdown Practice are detailed mathematically and finally correction factors for the different environmental conditions applied to averaged coastdown coefficients.

Chapter 8 discusses the software's that can be used in fuel economy calculations of the either light-duty or heavy-duty vehicles. AVL is the world's largest privately owned company for development of powertrains (combustion engines, hybrid systems, electric drive) as well as simulation and test systems for light-duty vehicles, heavy-duty vehicles and marine engines.[2]

Finally, a conclusion is drawn for the work presented in this thesis and recommendations for future research is expressed.

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[2] http://www.avl.com/wo/webobsession.servlet.go?app=bcms&page=view&nodeid=400013015

Chapter 2 Description of Vehicle Dynamics

2.1 OVERVIEW

In this section, details of the vehicle dynamics necessary for modeling fuel economy will be discussed. The scope of the study is for light-duty vehicles (LDVs) but introductory information for heavy-duty vehicles (HDVs) will also be presented.

To predict the vehicle performance in both the light-duty and heavy-duty classes, application of some fundamental principles of physics is required and this analysis is illustrated in the following subsections.

2.2 VEHICLE PERFORMANCE MODELING

Figure 2.1 is an illustration of the forces resisting the movement of a vehicle driving on a road at a steady speed. The total resistive force $\left(F_{res}\right)$ is the result of various individual forces that are additive. These forces are the aerodynamic drag force $\left(F_D\right)$ the rolling resistance $\left(F_R\right)$ and the force imposed by a grade $\left(F_G\right)$:

$$F_{res} = F_D + F_R + F_G \tag{2.1}$$

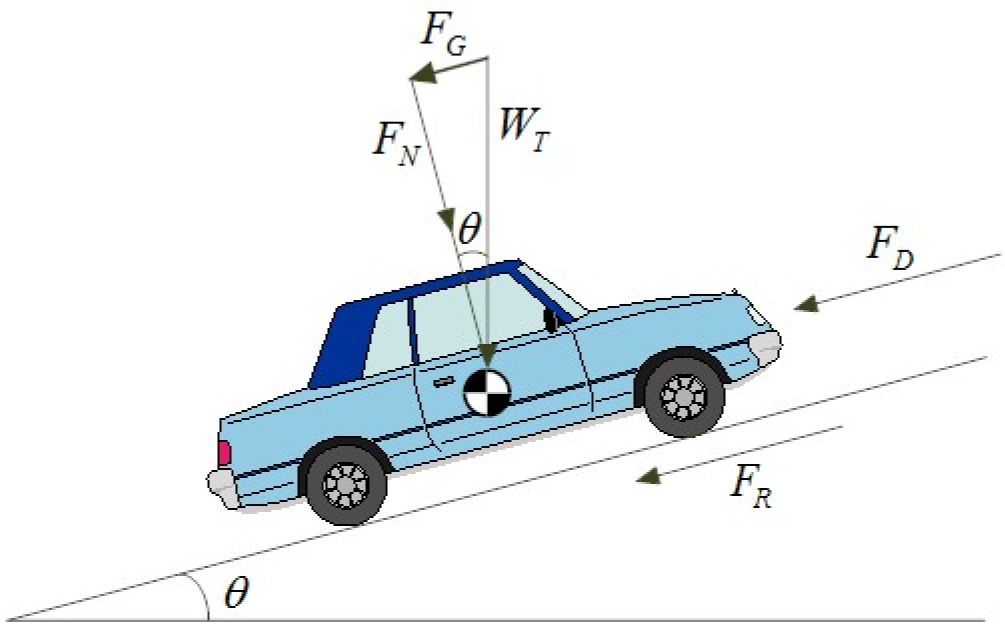

Figure 2.1 Forces acting on a vehicle driving at steady speed.

The aerodynamic drag force is due to the air moving around the vehicle and is experimentally measured in tests that are conducted in a wind tunnel. The rolling resistance expresses the frictional force acting between the tires and the road while the force imposed by a grade is the force of gravity acting on the vehicle while driving uphill or downhill.

2.3 TOTAL RESISTIVE FORCE

The resistive force implies that a certain power is required to move the vehicle at steady speed under given conditions of wind speed, vehicle speed, grade, etc. For driving at steady speed with no wind on a level road, the resistive force is called the road load force, as discussed in the following subsection.

2.4 ROAD LOAD POWER REQUIREMENT

One standard of vehicle performance is its behavior with no wind and no grade. This condition is known as "road load" and the corresponding resistive force is called the road load force $\left(F_{RL}\right)$. In terms of the fundamental physical parameters, the road load force is:

$$F_{RL} = \frac{1}{2}\rho_{air} C_D A V^2 + C_{RR} W_T \tag{2.2}$$

where ρ_{air} is the ambient air density, C_D is the drag coefficient of the vehicle, A is the front cross-sectional area of the vehicle, V is the vehicle speed, C_{RR} is the coefficient of rolling resistance between the tires and the road surface, and W_T is the total weight of the vehicle. At one time, every manufacturer who sold light-duty vehicles in the U.S. reported the values of C_D and C_{RR} to the EPA, who then published all of this data (in hard copy, before the web). These values were essential for setting the "absorption torque" on chassis dynamometers that were used to measure the fuel economy and/or emissions from that specific vehicle. However, there were inaccuracies in measuring the drag coefficient because, at the time, there were no "rolling road" wind tunnels to accurately simulate the aerodynamics of the flow under the vehicle. Also, the coefficient of rolling resistance is measured using a tire test machine in which a tire is rotating by a moving belt, the surface of which was intended to simulate the average road surface. The coefficient of rolling resistance is a function of the normal load on the tire (the fraction of the total vehicle weight supported by each tire), so a weighted average must be used to calculate C_{RR} for use in Equation (2.2). Furthermore, C_{RR} is a function of vehicle speed, tire inflation pressure, tire temperature, tire construction, and tire compound. Because the tests for C_D and C_{RR} were both expensive and involved inaccuracies and uncertainties, the Society of Automotive Engineers (SAE) developed a coastdown technique, as discussed in Subsection 2.5. Nevertheless, understanding the underlying physics is important.

The power required to provide the road load force is called the road load power (P_{RL}).

Road load power is useful for predicting "standard" vehicle performance under steady driving conditions. Here, it is important to note that P_{RL} is the power required at the interface between the drive tires and the road, and is not the brake power required of the engine to propel the vehicle at steady speed on a level road with no wind (bp_{RL}). The relationship between P_{RL} and bp_{RL} is discussed in Chapter 4.

2.5 COASTDOWN AND CHASSIS DYNO TESTS

For chassis dyno testing, such as for emissions certification and fuel economy tests, the resistive force is the force that must be absorbed by the dyno during prescribed accelerations, decelerations, and steady state cruises. For such tests, there is no wind and the vehicle speed is prescribed as a function of time, thus dictating the rate of change of speed (acceleration or deceleration) each second.

SAE Recommended Practice J1263 shows how on-road coastdown tests can be used to determine the road load coefficients. In practice, the coast-down data generally yields a second order fit that includes a term that is linear in vehicle speed:

$$F_{res} = M_e \frac{dV}{dt} + f_0 + f_1 V + f_2 V^2 \tag{2.3}$$

where f_1 may be non-zero due to the characteristics of the tires. In fact, the tires have a strong effect on the coast-down results. SAE Recommended Practice J2264 explains that such coast-down tests can also be used to determine the road load coefficients using modern electric chassis dynamometers. In this case, the coefficients from the on-road coast-down tests are used as "targets" for the initial chassis dyno coast-down tests. The resulting chassis dyno coast-down data are fitted with a quadratic equation that yields a term that is linear in vehicle speed:

$$F_{abs} = M_e \frac{dV}{dt} + A + BV + CV^2 \tag{2.4}$$

where coefficient B is required to compensate for internal friction in the dyno and for the characteristics of the tires, and F_{abs} is the same as F_{res}. If the coast-down tests are done properly, Equation (2.4) is more accurate than Equation (2.2) due to approximations in calculating the drag coefficient C_D and the coefficient of rolling resistance C_{RR} from wind tunnel test data and tire test machine data, as discussed previously. That is, due to approximations and assumptions in wind tunnel and tire machine tests, coast-down data such as used for Equation (2.4) can be more accurate than the more fundamental approach of Equation (2.2).

For emissions certification tests of light-duty vehicles, the EPA uses a test weight that is the curb weight plus 2548 N (300 lb). SAE Recommended Practice J2264 explains that the effective mass appearing in Equation (2.4) depends upon the purpose of the test. For determination of the road load coefficients A, B, and C, from coast-down tests, the effective mass is called the highway inertia. For general testing, the actual road load is desired - the rotational inertia of all four wheel assemblies must be accounted for. In this case, the highway inertia includes the test mass plus the effective masses of both the driven and non-driven wheel assemblies, and can be estimated as 1.03 times the vehicle test mass for vehicles with only four tires. For certification purposes, the highway inertia is dictated by regulations to be the effective test mass (an effective test weight, ETW, is assigned for a vehicle to represent a class of vehicles) plus the effective masses of only the driven wheel assemblies, and can be estimated as 1.015 times the ETW/g for vehicles with only two driven tires. When the chassis dyno is being used to control the vehicle resistance, the effective mass in Equation (2.4) is called the inertia mass and, again, there are two cases. For general testing it is recognized that only two wheel assemblies are rotating during chassis dyno testing. In this case, the inertia mass includes the test mass plus the effective masses of only the driven wheel assemblies, and can be estimated as 1.015 times the vehicle test mass for vehicles with only two driven tires. For tests that are dictated by regulations such as emissions certification and urban and highway fuel economy, the effective mass equals the ETW/g. To calculate the fuel economy (or emissions) of a specific vehicle, as needed for this project, the effective mass is the curb weight plus the payload weight (driver, cargo, etc.) plus the mass of all of the wheel assemblies that rotate when the vehicle is driving down a road.

Chapter 3 Engine Performance

3.1 OVERVIEW

The fundamental equations governing vehicle dynamics were explained in Chapter 2 and now it is time to examine the engine which is the power source to overcome the resistive forces that nature imposes. The most widely used engine on the roads nowadays is the gasoline engine, widely called the Spark Ignition (SI) engines. Parameters defined in this chapter are applicable to diesel engines also but some modifications to the equations may be required for such special cases.

By the advance of the technology, engine control strategies are changing by time in addition to fuel injection systems and the materials used. However the fundamental principle of the gasoline engine did not change much since Otto's first engine. The following subsections are going to provide some definitions and the governing equations that are required by the fuel economy model. A full detailed parameter analysis can be found at Matthews, 2007.

3.2 POWER

Torque and rotational speed (revolution per minute – rpm) can be measured by using a machine called a dynamometer or dyno for short. The engine is placed on a test bed and connected to the dyno by a coupling. Figure 3.1 shows the engine and dyno setup.

Early dynamometers were called brakes since they used brake shoes to press against the flywheel to apply the desired load (Obert, 1973). This explains the current use of "brake power" and "brake torque" that refer to power and torque readings at the engine output shaft as obtained from a dyno.

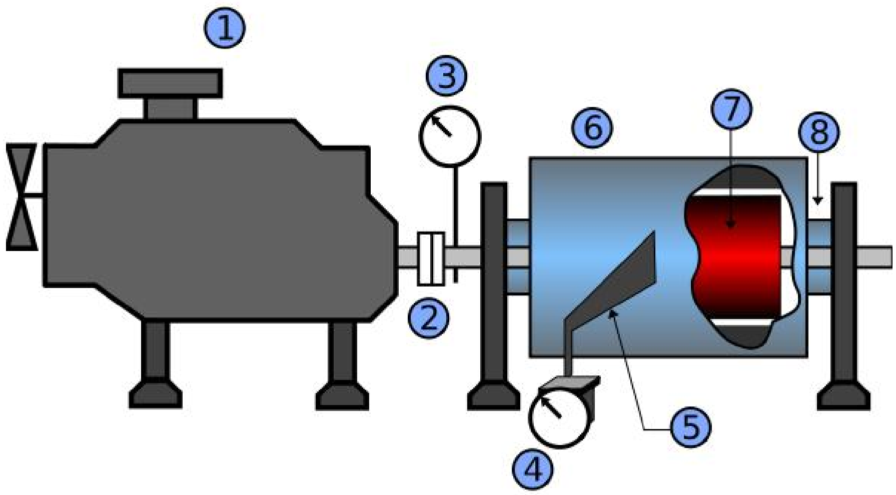

Figure 3.1 Engine connected to the dynamometer by coupling[3]

Table 3-1 summarizes the part names of the engine and dyno system shown in Figure 3.1.

Table 3-1 Part names in Figure 3.1

Part Number	Name
1	Engine
2	Coupling
3	Tachometer
4	Scales
5	Torque Arm
6	Stator (Housing)
7	Rotor
8	Bearings

The rotor is coupled to the stator, as shown in Figure 3.2, by means of hydraulic, electromagnetic or mechanical forces. In general the torque exerted on the stator by the

[3] http://en.wikipedia.org/wiki/Dynamometer

rotating rotor is balanced with some means of restraining the rotation of the stator while also measuring the restraining force.

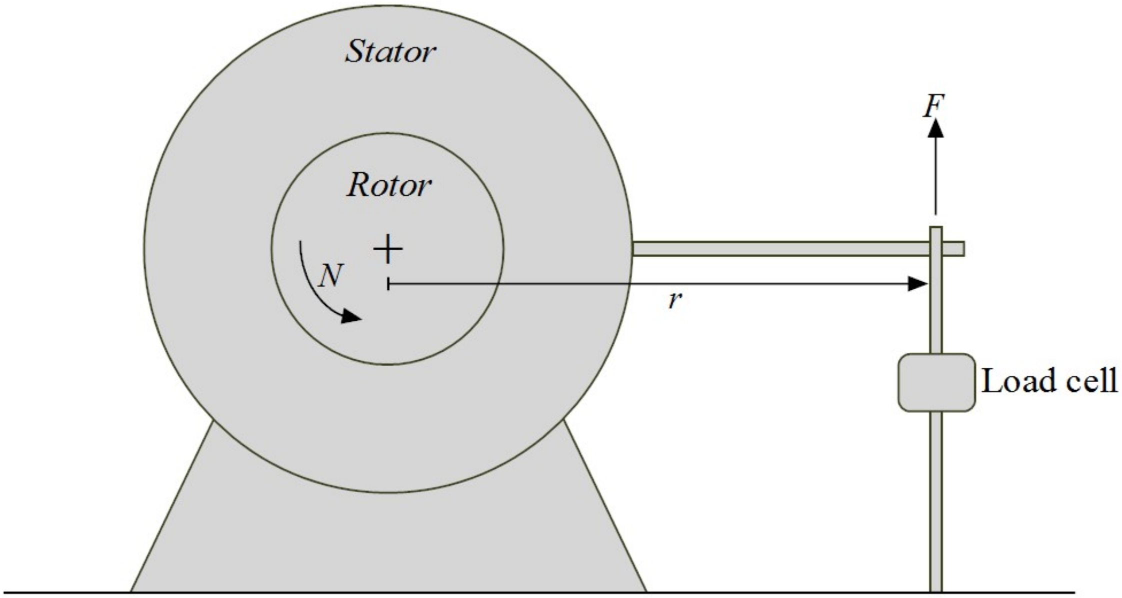

Figure 3.2 Schematic of principle of operation of dynamometer[4]

The torque τ, produced by the engine can be calculated as force F times the torque arm r as shown in Figure 3.2.

$$\vec{\tau} = \vec{F} \times \vec{r} \tag{3.1}$$

The power p produced by the engine and absorbed by the dynamometer is the product of torque and angular speed:

$$p = \tau\left(2\pi N\right) \tag{3.2}$$

where N is the engine crankshaft rotational speed.

[4] J. B. Heywood, Figure 2-3

If the engine is running in steady state operation and the dynamometer is in the absorption mode then the power described by Equation (3.2) is called the "brake power, bp".

$$bp = 2\pi\tau N \tag{3.3}$$

3.3 STOICHIOMETRY

During engine operation, both the fuel mass flow rate, $\dot{m}_f$,and the air mass flow rate, $\dot{m}_a$,are measured and these parameters control the power output of the engine. In order to maintain stable combustion, homogenous charge SI engines must maintain an almost constant, usually stoichiometric mixture.

The ratio of the fuel mass flow rate to the air mass flow rate defines the fuel/air ratio (FA) and air/fuel ratio (AF) vice versa.

$$Fuel/air\ ratio(FA) = \frac{\dot{m}_f}{\dot{m}_a} \tag{3.4}$$

$$Air/fuel\ ratio(AF) = \frac{\dot{m}_a}{\dot{m}_f} \tag{3.5}$$

In addition to the air/fuel ratio and fuel/air ratio, the automotive industry accepts other ways of defining this ratio as standard depending upon preferences. The air/fuel ratio is a number that sits between 12 and 18 for most of the SI engines while the fuel/air ratio is just the inverse of the air/fuel ratio - that is, a number between 0.056 and 0.083. The air/fuel ratio is widely used because of its meaningful range of numbers.

In addition to monitoring a state of the engine, it is also useful to compare that state with a stoichiometric state. To achieve this, another parameter called the equivalence ratio, ϕ, is introduced. The equivalence ratio of the engine is defined as the ratio of fuel/air ratio to the stoichiometric fuel/air ratio. Mathematically,

$$\phi = \frac{FA}{FA_s} = \frac{AF_s}{AF} \tag{3.6}$$

For stoichiometric combustion, $\phi = 1.0$ and the equivalence ratio is greater than 1.0 for rich combustion and it is smaller than 1.0 for fuel lean combustion, respectively.

3.4 MEAN EFFECTIVE PRESSURE

The mean effective pressure is a parameter related to internal combustion operation and is a measure of ability to do work and it is a benchmark parameter to compare engines irrespective of their displacement, engine speed and whether the engine is a four stokes or two strokes or even a Wankel engine. The mean effective pressure is also a more fundamental metric for the load on an engine than is the power or torque.

While an engine is working, the pressure inside the combustion chamber is continuously changing from atmospheric pressure (or less) to 30 times atmospheric pressure or more depending upon the load and air entering the combustion chamber. The "indicated" mean effective pressure $(imep)$ may be thought of as the average pressure over a cycle in the combustion chamber of the engine that produces the same work over the same power stroke as the variable pressure over the whole engine cycle. The "brake" mean effective pressure uses the same normalization but is from the perspective of the engine output shaft.

Force can be written as pressure times the cross sectional area for a piston system as well known from physics:

$$F = P \times A \tag{3.7}$$

Work can be defined as the amount of energy transferred by a force acting through a distance and can be expressed as:

$$W = \int F ds \tag{3.8}$$

where F is the force vector and s is the position vector. By inserting Equation (3.7) into Equation (3.8), one gets:

$$W = \int PAds \tag{3.9}$$

The mean effective pressure and cross-sectional area for a cylinder will be constant, therefore those terms can go out from the integral and we are just left with the term $\int ds$.

This term is just the stroke of the piston.

$$W = PAS \tag{3.10}$$

where S is the stroke or linear distance travelled by the piston from top death center (TDC) to bottom death center (BTC) and the actual variable P can be replaced by the constant $imep$.

Therefore, the indicated work per cylinder per power stroke can be written as:

$$W_{ind} = imep \times A \times S = imep\left(V_{max} - V_{min}\right) = imep \times V_s \tag{3.11}$$

where, V_s is the swept volume, or displacement per cylinder.

Multiplying Equation (3.11) by the number of cylinders, n, by the engine speed, N, and by the number of power strokes per crankshaft revolution, $1/x$, gives an expression for the indicated power, ip (the power from the working fluid's perspective, at the top of the piston):

$$ip = imep\left[ASn\right]\frac{N}{x} = imep\left[D\right]\frac{N}{x} \tag{3.12}$$

where:

$x = 2$ for a 4-stroke piston engine
$x = 1$ for a rotary engine (4-stroke)
$x = 1$ for a 2-stroke engine

The term in brackets on the right hand side is the engine displacement, D. By rearranging Equation (3.12), one can express the mean effective pressure as:

$$mep = \frac{px}{DN} \tag{3.13}$$

Substitution of either the brake power, the indicated power, or the friction power into Equation (3.13) yields expressions for the brake mean effective pressure $(bmep)$, the indicated mean effective pressure $(imep)$, and the friction mean effective pressure $(fmep)$ respectively:

$$bmep = \frac{bp\ x}{D\ N} \tag{3.14}$$

$$imep = \frac{ip\ x}{D\ N} \tag{3.15}$$

$$fmep = \frac{fp\ x}{D\ N} \tag{3.16}$$

3.5 SPECIFIC FUEL CONSUMPTION

Fuel consumption is measured as a flow rate but it is not directly comparable among different engine sizes and load conditions. Another term called the specific fuel consumption, sfc, allows the fuel efficiency of different internal combustions engines to be directly compared. It measures how efficiently an engine is using the fuel supplied to produce work:

$$sfc = \frac{\dot{m}_f}{p} \tag{3.17}$$

Both the brake specific fuel consumption, $bsfc$, and the indicated specific fuel consumption, $isfc$, can be defined through the appropriate substitutions into Equation (3.17):

$$bsfc = \frac{\dot{m}_f}{bp} \tag{3.18}$$

$$isfc = \frac{\dot{m}_f}{ip} \tag{3.19}$$

3.6 OVERALL ENGINE EFFICIENCY

The ratio of the work produced per cycle to the amount of fuel energy supplied per cycle with fuel during combustion can be used as a measure of the overall engine efficiency. Thermodynamically, efficiency is a dimensionless performance measure and is defined as the ratio of "what you get" to "what you pay for". What we get in an internal combustion engine is the power output of the engine, which is basically brake power and what we pay for is the chemical energy in the fuel. The maximum rate of energy released from the fuel in the combustion process can be calculated by multiplying the mass flow rate of the fuel per cycle with the constant pressure Lower Heating Value of the fuel, LHV_P. Thus the overall engine efficiency is:

$$\eta_e = \frac{bp}{\dot{m}_f LHV_P} \tag{3.20}$$

The maximum energy release in the combustion process can be attained with complete combustion and constant pressure combustion in a flow calorimeter. The Lower Heating Value is used rather than the Higher Heating Value for the practical reason that condensation of water in the combustion chamber must be avoided.

By inserting Equation (3.18) into Equation (3.20), one can see the effect of specific fuel consumption on the overall engine efficiency (sometimes called the brake thermal efficiency):

$$\eta_e = \frac{1}{bsfc \times LHV_P} \tag{3.21}$$

Most transportation fuels are mixtures of many chemical species plus additives, and their composition may be changed by time of the year and tank to tank. Therefore there is a great variety among Heating Values and that makes comparison of overall engine efficiencies difficult. However, as can be seen from Equation (3.21), lower specific fuel consumption corresponds to higher overall engine efficiency, as expected.

3.7 FUNDAMENTAL ENGINE EFFICIENCIES

It is desirable to express the engine performance parameters discussed above in terms of the engine design and operating conditions that control them. The mathematical relationships developed in this section (Matthews, 1983) may be used to enhance physical understanding of the factors that affect the engine's performance.

3.7.1 Indicated Thermal Efficiency

The word "indicate" is described as "to point out or point to with more or less exactness" in Webster's Dictionary. If this definition is applied to the engine context, one can use it for the terms which are results of the working fluid itself. Power is produced by the working fluid (which is called the indicated power) but, due to frictional, viscometric, and parasitic the losses between the working fluid space and the engine output shaft (referred to as the friction power), one ends up with the brake power at the engine output shaft.

In classical thermodynamics, a thermal efficiency is defined as the ratio of the useful work (which is the net work done by the system, from the working fluid's perspective) to the thermal energy added to the working fluid. Beware that thermal energy term is not "net", because what we pay for is the chemical energy content of the fuel. Mathematically one can write:

$$\eta_t = \frac{W_{net}}{Q_{in}} = \frac{p_{net}}{\dot{Q}_{in}} \tag{3.22}$$

Equation (3.22) can be more precisely defined as the "indicated thermal efficiency" since it is the efficiency - before the losses in the engine - from the working fluid's perspective.

$$\eta_{it} = \frac{ip}{\dot{Q}_{in}} \tag{3.23}$$

3.7.2 Combustion Efficiency

Combustion efficiency is defined as the ratio of the thermal energy ("heat") transferred to the working fluid after combustion to the maximum heat release from that combustion. As explained in Section 3.6, the maximum heat release occurs for complete combustion of a lean or stoichiometric mixture. Thus, the maximum heat release rate is quantified as the fuel mass flow rate time the constant pressure Lower Heating Value, LHV_P, of the fuel (which is the chemical energy of fuel – what the consumer actually pays for):

$$\dot{Q}_{\max} = \dot{m}_f LHV_P \tag{3.24}$$

Therefore, the combustion efficiency can be written as:

$$\eta_c = \frac{\dot{Q}_{in}}{\dot{Q}_{\max}} = \frac{\cancel{\dot{m}_f}\, q_{in}}{\cancel{\dot{m}_f}\, LHV_P} = \frac{q_{in}}{LHV_P} \tag{3.25}$$

where q_{in} is the actual thermal energy transferred to the working fluid by combustion per unit mass of fuel.

One can relate the indicated thermal efficiency with the combustion efficiency by using the common term $\dot{Q}_{in}$ in Equations (3.23) and (3.25).

$$\dot{Q}_{in} = \frac{ip}{\eta_{it}} = \eta_c \dot{Q}_{\max} \tag{3.26}$$

$$ip = \eta_{it}\eta_c \dot{Q}_{\max} \tag{3.27}$$

By inserting Equation (3.24) for the $\dot{Q}_{\max}$ term in Equation (3.27):

$$ip = \eta_{it}\eta_c \dot{m}_f LHV_P \tag{3.28}$$

3.7.3 Volumetric Efficiency

The intake system of the engine includes parts like an air filter, throttle body, intake manifold, intake ports, and intake valves that restrict the air to flow freely to the combustion chamber. The volumetric efficiency is used to measure how efficiently an engine can induct the air into the combustion chamber. The volumetric efficiency is defined as the ratio of the air mass actually entered to the maximum theoretical air mass that can be filled into the cylinders volume. This maximum mass of air is basically the total engine cylinder volume or basically engine displacement times the density of the air per engine revolution. Mathematically:

$$\eta_v = \frac{\dot{m}_a}{\dot{m}_{a,theoeretical}} \tag{3.29}$$

$$\dot{m}_{a,theoeretical} = \frac{\rho_{air} DN}{x} \tag{3.30}$$

where ρ_{air} is the air density at the inlet of the carburetor or throttle body, D is the engine displacement, N is the engine rotational speed, and x is the number of crankshaft revolutions per intake stroke.

$$\eta_v = \frac{\dot{m}_a}{\frac{\rho_{air} DN}{x}} \tag{3.31}$$

Note that the volumetric efficiency is not a real efficiency like the previous efficiencies since it does not contain any power or heat transfer rate terms. Therefore, one cannot expect it to stay between 0 and 1, indeed in many cases the volumetric efficiency is over 1.

By using Equations (3.4) and (3.6), one can express the mass flow rate of the fuel in terms of the air mass flow rate and equivalence ratio:

$$FA = \frac{\dot{m}_f}{\dot{m}_a} = \phi FA_s \tag{3.32}$$

$$\dot{m}_f = \dot{m}_a \phi FA_s \tag{3.33}$$

Substituting Equation (3.33) back into Equation (3.28) yields:

$$ip = \eta_{it} \eta_c \dot{m}_a \phi FA_s LHV_P \tag{3.34}$$

By using Equation (3.31), substituting the air mass flow rate $\dot{m}_a$ in terms of the volumetric efficiency and related engine parameters:

$$ip = \eta_{it} \eta_c \left(\eta_v \frac{\rho_a DN}{x} \right) \phi FA_s LHV_P \tag{3.35}$$

Rearranging terms yields:

$$ip = \eta_{it}\eta_c\eta_v\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P \quad (3.36)$$

Similarly, the fuel mass flow rate can be written by combining Equations (3.31) and (3.33):

$$\dot{m}_f = \eta_v \frac{\rho_a DN}{x}\phi FA_s \quad (3.37)$$

Rearranging yields:

$$\dot{m}_f = \eta_v \rho_a D\left(\frac{N}{x}\right)\phi FA_s \quad (3.38)$$

Equation (3.36) is a very useful equation since it relates three fundamental efficiencies of the engine with the potential ability of an engine to do work. Further fundamental relations can be retrieved by back inserting Equation (3.36) into Equation (3.15).

$$imep = \frac{\eta_{it}\eta_c\eta_v\rho_a \cancel{D}\left(\frac{\cancel{N}}{\cancel{x}}\right)\phi FA_s LHV_P \cancel{x}}{\cancel{D}\ \cancel{N}} \quad (3.39)$$

$$imep = \eta_{it}\eta_c\eta_v\rho_a\phi FA_s LHV_P \quad (3.40)$$

Equation (3.40) shows that the indicated mean effective pressure is not a direct function of engine displacement, engine speed, or whether the engine is a 4-stroke, a 2-stroke, or a Wankel (via x, the number of revolutions per power stroke).

Another fundamental equation can be obtained via inserting Equations (3.36) and (3.38) into Equation (3.19) for the indicated specific fuel consumption $isfc$:

$$isfc = \frac{\dot{m}_f}{ip} = \frac{\cancel{\eta_v\rho_a D\left(\frac{N}{x}\right)\phi FA_s}}{\eta_{it}\eta_c\ \cancel{\eta_v\rho_a D\left(\frac{N}{x}\right)\phi FA_s}\ LHV_P} \quad (3.41)$$

$$isfc = \frac{1}{\eta_{it}\eta_c LHV_P} \quad (3.42)$$

3.7.4 Mechanical Efficiency

In engine operation, there are power losses due to friction in bearings of the crankshaft, friction between the pistons, and the cylinder walls, and other miscellaneous mechanical losses, such as the power required to run the oil pump. All of these losses combine to constitute the friction power, which is basically the difference between the indicated power and the brake power.

$$ip = bp + fp \tag{3.43}$$

The mechanical efficiency, η_m can be defined as the efficiency of converting the net power available from the working fluid to available power at the output of the crankshaft:

$$\eta_m = \frac{bp}{ip} = 1 - \frac{fp}{ip} \tag{3.44}$$

The mechanical efficiency can be written in terms of mean effective pressures by using Equations (3.14), (3.15), and (3.16):

$$\eta_m = \frac{\dfrac{bmep \times \cancel{D \times N}}{\cancel{x}}}{\dfrac{imep \times \cancel{D \times N}}{\cancel{x}}} = 1 - \frac{\dfrac{fmep \times \cancel{D \times N}}{\cancel{x}}}{\dfrac{imep \times \cancel{D \times N}}{\cancel{x}}} \tag{3.45}$$

After cancelling the same terms:

$$\eta_m = \frac{bmep}{imep} = 1 - \frac{fmep}{imep} \tag{3.46}$$

Substituting Equation (3.44) into Equation (3.36) yields:

$$\frac{bp}{\eta_m} = \eta_{it}\eta_c\eta_v\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P \tag{3.47}$$

Rearranging:

$$bp = \eta_{it}\eta_c\eta_v\eta_m\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P \tag{3.48}$$

Substitution of Equation (3.48) into Equation (3.14) and Equation (3.18) yields fundamental relationships for the brake mean effective pressure and brake specific fuel consumption:

$$bmep = \frac{\eta_{it}\eta_c\eta_v\eta_m\rho_a \cancel{D}\left(\frac{\cancel{N}}{\cancel{x}}\right)\phi FA_s LHV_P \cancel{x}}{\cancel{D}\ \cancel{N}} \tag{3.49}$$

$$bmep = \eta_{it}\eta_c\eta_v\eta_m\rho_a\phi FA_s LHV_P \tag{3.50}$$

$$bsfc = \frac{\dot{m}_f}{\eta_{it}\eta_c\eta_v\eta_m\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P} \tag{3.51}$$

Inserting Equation (3.38) into Equation (3.51):

$$bsfc = \frac{\cancel{\eta_v}\ \cancel{\rho_a D\left(\frac{N}{x}\right)\phi FA_s}}{\eta_{it}\eta_c\ \cancel{\eta_v}\ \eta_m\ \cancel{\rho_a D\left(\frac{N}{x}\right)\phi FA_s}\ LHV_P} \tag{3.52}$$

$$bsfc = \frac{1}{\eta_{it}\eta_c\eta_m LHV_P} \tag{3.53}$$

The overall engine efficiency can be obtained in terms of other engine efficiencies by inserting Equations (3.38) and (3.48) into Equation (3.20):

$$\eta_e = \frac{\eta_{it}\eta_c\ \cancel{\eta_v}\ \eta_m\ \cancel{\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P}}{\cancel{\eta_v}\ \cancel{\rho_a D\left(\frac{N}{x}\right)\phi FA_s LHV_P}} \tag{3.54}$$

$$\eta_e = \eta_{it}\eta_c\eta_m \tag{3.55}$$

3.8 SUMMARY

This chapter was intended to familiarize reader with the engine parameters and show a fundamental approach to derive governing equations in the engine operation. By using the fundamental equations derived in this chapter, one can model the consumption of fuel at different operating ranges as it will be shown in Chapter 4 and Chapter 5. Moreover, these equations are useful for comparison of different types of the engines performance characteristics wise or fuel economy point of view.

Chapter 4 Fuel Economy Model: A Vehicle Class Approach

4.1 OVERVIEW

The Environmental Protection Agency (EPA) fuel economy estimates have appeared on the window stickers since the late 1970's and well-recognized by the customers[5]. The fuel economy estimates have two major uses: one is providing consumers a benchmark to compare vehicles during the buying process and giving an idea of how much fuel economy they would expect while using that specific vehicle.

EPA made some changes to the methods used to calculate fuel economy (FE) estimates that are posted on window stickers of all new cars and light trucks sold in the United States. The aim of this method is to estimate real world conditions i.e. aggressive acceleration and deceleration, use of air conditioning, and operation in cold temperatures. According to final rule posted on Federal Register (Vol.71, No. 248 / December 27, 2006), the city miles per gallon (mpg) estimates for the manufacturers of most vehicles will drop by about 12 percent on average relative to today's estimates, and city mpg estimates for some vehicles will drop by as much as 30 percent. The highway mpg estimates for most vehicles will drop on average by about 8 percent, with some estimates dropping by as much as 25 percent relative to today's estimates. Table 4-1 shows the change in fuel economy in classes for new fuel economy calculation method compared to old method.

[5] EPA420-R-06-017

Table 4-1 Current and 5-Cycle Label Fuel Economies by Model Type[6]

	Current City	5-Cycle City	Current Highway	5-Cycle Highway
Conventional Vehicles				
Large car	15.7	13.8	21.9	19.7
Midsize car	20.5	17.8	27.9	25.6
Minivan	17.4	15.2	23.6	20.9
Pickup	15.1	13.2	18.9	17.2
Small car	20.7	18.1	27.3	25.3
Station wagon	20.3	17.6	26.6	23.5
SUV	16.8	14.6	21.6	19.5
Van	12.5	10.9	16	14.3
All conventional	**18.6**	**16.2**	**24.6**	**22.4**
All hybrids	41.6	32	40.6	36.8
Diesel (one midsize car)	26.2	22.7	35.3	31.4
All vehicles	**19.1**	**16.4**	**24.9**	**22.7**

The previous method was established in 1984 by adjusting the city test result (Federal Test Procedure – FTP) 10 percent downward and the highway test result (Highway Fuel Economy Test – HFET) 22 percent downward. In 2008 method of EPA, additional tests are incorporated to represent today's driving style which includes higher speeds, aggressive acceleration and deceleration, air conditioner usage and cold air conditions. Clearly FTP and HFET do not capture the real world driving conditions; therefore FTP, HFET, US06, SC03 and Cold FTP combined. EPA refers to this test as "5-cycle" method; however in our mechanistic model FTP and Cold FTP are same so

[6] EPA420-R-06-017

basically in our method cold start conditions are not represented as it is intended by EPA. The five test procedures are summarized in the following table:

Table 4-2 Characteristics of the fuel economy and emissions tests of the 5-cycle methodology[7]

Test	Designed to represent	Avg speed (mph)	Max speed (mph)	Max accel (mph/sec)	Ambient conditions	Primary use
Federal Test Procedure (FTP).	Urban stop-and-go driving from 1970's.	21	58	3.3	75 °F	Emissions & fuel economy testing.
Highway Fuel Economy Test (HFET).	Rural driving	48	60	3.3	75 °F	Fuel economy testing.
US06	High speeds and aggressive driving.	48	80	8.5	75 °F	Emissions testing.
SC03	Air conditioner operation.	22	55	5.1	95 °F & 40% relative humidity.	Emissions testing.
Cold FTP	Cold temperature operation.	21	58	3.3	20 °F	Emissions testing.

With changes in calculation method in 2008, EPA also changed fuel economy label design as it is shown in Figure 4.1.

The label shows the estimated city mpg at the top left, and highway mpg at the top right and below these estimates there is another estimate depending upon driver habits what kind of mpg values would consumer expect. The center of the label provides estimated annual fuel costs based on a given number of miles and fuel price also listed on the label. This information is very useful to understand the operating cost of that vehicle and stands as a benchmark economy wise. The lower center of the label gives a combined city/highway estimate for that vehicle, and shows where that value falls on a bar scale that gives the highest and lowest fuel economy of all other vehicles in its class.

[7] Federal Register, Vol. 71, No. 248, Table I-1

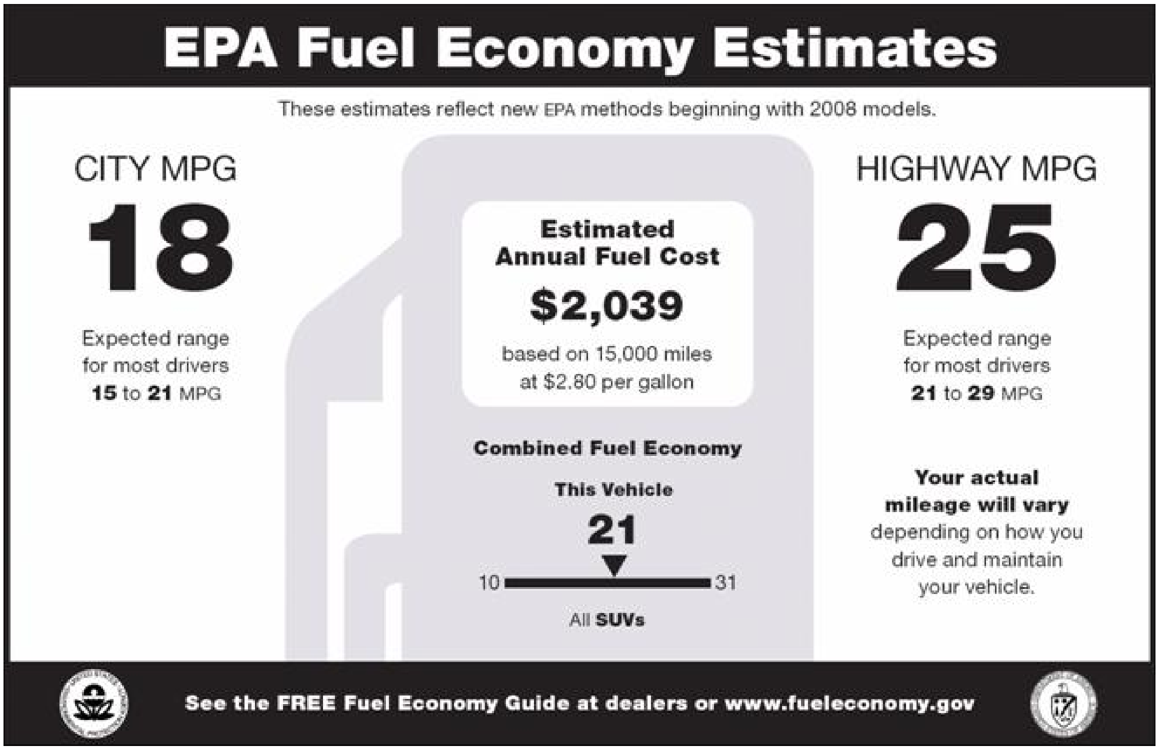

Figure 4.1 New EPA Fuel Economy Label[8]

4.2 LIGHT-DUTY VEHICLE CLASSIFICATION

Light-duty vehicle (LDV) regulations are divided into those applicable to passenger cars and those applicable to light-duty trucks. Light-duty trucks are defined as trucks of less than 8500 lbs Gross Vehicle Weight Rating (GVWR or GVW) after 1979, except for those with more than 45 ft^2 frontal area. Light-duty trucks were classified as heavy-duty vehicles in the Clean Air Act but are treated as LDVs by the U.S. Environmental Protection Agency (EPA) as far as test procedures are concerned. Federally, light-duty trucks are divided into light light-duty trucks (LLDTs) and heavy light-duty trucks (HLDTs) in four categories, with separate emissions standards for each

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[8] http://www.epa.gov/fueleconomy/420f06069.htm

category. The categories are based upon Loaded Vehicle Weight (LVW, curb weight + 300 lb), Gross Vehicle Weight Rating, and/or Adjusted Loaded Vehicle Weight $\left(ALVW = \frac{(LVW + GVWR)}{2} \right)$. LLDTs are divided into two categories: LDT1s and LDT2s, both of which have GVWR $<$ 6000 lb. HLDTs are also divided into two categories: LDT3s and LDT4s both of which have $6000 < \text{GVWR} \leq 8500$ lb. Beginning in 2004, a new federal vehicle category was introduced: the medium-duty passenger vehicle (MDPV). This category was designed to bring large passenger vehicles (such as large SUVs and passenger vans) over 8500 lbs GVWR into the "Tier 2" emissions standard program. MDPVs are defined as any complete heavy-duty vehicle less than 10,000 lbs GVWR designed primarily for transportation of people.

U.S. Department of Transportation (DOT) ruled to integrate medium-duty passenger vehicles (MDPV), including large SUVs and vans, into the Corporate Average Fuel Economy (CAFE) program starting in 2011; EPA must now include these vehicles in the fuel economy labeling program. Thus, EPA will be requiring fuel economy labeling of certain passenger vehicles up to 10,000 lb gross vehicle weight rating (GVWR). These vehicles used to be exempt because they weighed more than the previous cut-off of 8,500 lb. Vehicle manufacturers will be required to post fuel economy labels on MDPVs beginning with the 2011 model year.

Table 4-3 Vehicle categories used in EPA Tier 2 standards[9]

Vehicle Category			Abbreviation	Requirements
Light-Duty Vehicle			**LDV**	max. 8500 lb GVWR
Light-Duty Truck			**LDT**	max. 8500 lb GVWR, max. 6000 lb curb weight and max. 45 ft^2 frontal area
	Light light-duty truck		*LLDT*	GVWR < 6000 lb
		Light-duty truck 1	LDT1	LVW[1] < 3750 lb
		Light-duty truck 2	LDT2	3751 lb < LVW[1] < 5750 lb
	Heavy light-duty truck		*HLDT*	6000 lb < GVWR ≤ 8500 lb
		Light-duty truck 3	LDT3	3751 lb < ALVW[2] < 5750 lb
				5751 lb < ALVW[2] < 8550 lb
		Light-duty truck 4	LDT4	min. 5750 lb ALVW[2]
Medium-Duty Passenger Vehicle			**MDPV**	8500 lb < GVWR[3] < 10000 lb

1 - LVW (loaded vehicle weight) = curb weight + 300 lb

2 - ALVW (adjusted loaded vehicle weight) = average of GVWR and curb weight

3 - Manufacturers may alternatively certify engines for diesel fueled MDPVs through the heavy-duty diesel engine regulations

[9] http://www.dieselnet.com/standards/us/ld_t2.php

4.3 MATHEMATICAL MODEL

The steady state or when vehicle is not undergoing rapid changes in speed, fuel economy of the vehicle $\left[{}^{mi}\!/_{gal}\right]$ is the ratio of the vehicle speed $\left[{}^{mi}\!/_{hr}\right]$ to the volumetric rate of fuel consumption $\left[{}^{gal}\!/_{hr}\right]$.

$$FE\left[{}^{mi}\!/_{gal}\right] = \frac{V\left[{}^{mi}\!/_{hr}\right]}{\dot{V}_f\left[{}^{gal}\!/_{hr}\right]} \tag{4.1}$$

Equation (4.1) can also be written in terms of fuel density and fuel mass flow rate:

$$FE = \frac{V\rho_f}{\dot{m}_f} \tag{4.2}$$

Furthermore it is already known from Equations (3.18) and (3.53) that:

$$bsfc = \frac{\dot{m}_f}{bp} = \frac{1}{\eta_{it}\eta_c\eta_m LHV_P} \tag{4.3}$$

Rearranging yields:

$$\dot{m}_f = bsfc \cdot bp = \frac{bp}{\eta_{it}\eta_c\eta_m LHV_P} \tag{4.4}$$

Substituting back into Equation (4.2) yields:

$$FE = \frac{V\rho_f}{\dot{m}_f} = \frac{V\rho_f}{\frac{bp}{\eta_{it}\eta_c\eta_m LHV_P}} \tag{4.5}$$

Rearrange to get:

$$FE = \eta_{it}\eta_c\eta_m LHV_P\rho_f\left[\frac{V}{bp}\right] \tag{4.6}$$

The engine supplies power to overcome resistive forces explained in Chapter 2. Engine power available at the output of the crankshaft is called brake power, bp and this power first passes through transmission and differential then become available at the tires to push the vehicle forward and this available power at the tires is called the motive power, p_{mot}. The motive power that is available at the drive tires is basically the engine brake power minus the energy losses in the transmission and differential respectively. By using the transmission and differential efficiencies, one can write:

$$p_{mot} = bp \cdot \eta_t \cdot \eta_d \tag{4.7}$$

where bp is the brake power available at the crankshaft, η_t is the transmission efficiency, and η_d is the differential efficiency.

Motive force F_{mot} can be also calculated from motive power since it is well known that power is the time rate of work which indicates power is the force time speed:

$$p_{mot} = F_{mot} V \tag{4.8}$$

The term in brackets in Equation (4.6) can be expressed by Equations (4.7) and (4.8) as:

$$F_{mot} V = bp \cdot \eta_t \cdot \eta_d \tag{4.9}$$

$$\left[\frac{V}{bp}\right] = \frac{\eta_t \cdot \eta_d}{F_{mot}} \tag{4.10}$$

Substituting back into Equation (4.6) yields:

$$FE = \eta_{it} \eta_c \eta_m LHV_P \rho_f \left[\frac{\eta_t \cdot \eta_d}{F_{mot}}\right] \tag{4.11}$$

Under steady state road load conditions, this becomes:

$$FE = \eta_{it} \eta_c \eta_m LHV_P \rho_f \left[\frac{\eta_t \cdot \eta_d}{F_{RL}}\right] \tag{4.12}$$

Equation (4.12) can be manipulated to yield:

$$FE = \frac{[\eta_e \cdot \eta_{dt}]}{F_{RL}} \left(\rho_f \cdot LHV_p\right) \tag{4.13}$$

where η_e is the overall engine efficiency, η_{dt} is overall drivetrain efficiency, ρ_f is fuel density, and LHV_p is the energy density of the fuel.

Equation (4.13) is the base equation for both LDV's and HDV's. Fuel property effects can be easily found from thermodynamic tables. Equation (2.4) estimates the road load force where coefficients are EPA target values. Only left part is product of efficiencies: $\eta_e \times \eta_{dt}$.

The product depends upon both engine speed and torque and will require calibration against experimental data. Fortunately, this product can be back-calculated from the "unadjusted" urban and highway fuel economy for a variety of vehicles from the data in EPA's Fuel Economy Guide (www.epa.gov/fueleconomy). The FTP (urban fuel economy) and HFET (highway fuel economy) is available in excel spreadsheets. The fuel economy will be calculated in each second, using a user-specified constant for $\eta_e \times \eta_{dt}$.

After calculating the FE in each second, the distance travelled during that second is calculated, and this is used to calculate the gallons of fuel used during that second. At the end of the driving cycle, sum up the gallons of fuel consumed, and add together the miles traveled, and calculate the ratio: the FE $\left[{}^{mi}\!/\!_{gal}\right]$ for this driving cycle. The value of adjustable constant $\left(\eta_e \times \eta_{dt}\right)$ that provides the best agreement with the data is the calibrated value to be used for that class of vehicle.

4.3.1 LDV Fuel Economy

1) There is some imprecision for each category of LDV due to the necessity of using average values for each class of vehicle. It is also necessary to "filter" EPA's data.
2) Extrapolation to alternative fuels will be simple since density and lover heating value can be easily inserted in the fuel economy calculation through Equation (4.13).
3) Experimental data can be used to calculate coastdown coefficients as it is explained in Chapter 6 and Chapter 7.

4.3.2 HDV Fuel Economy

HDV's are not subjected to FE standards and there is no EPA data that will be useful to this study from the HDV perspective.

Because truck manufacturers generally offer a choice of engines from 2 or more manufacturers, and because a specific engine from an engine manufacturer may be used in a variety of applications, the engines are subjected to emissions regulations and the certification tests are done using an engine dyno instead of a chassis dyno.

However, Equation (4.13) is still valid and can be used for the HDV fuel economy calculation with some difference from the LDV part. Instead of Equation (2.4) to estimate road load force, fundamental approach can be used; which is Equation (2.1). Equation (2.1) can be written in advanced form as:

$$F_{RL} = \frac{1}{2}\rho_{air} C_D A V^2 + C_{RR} W_T \pm W_T \sin\theta \tag{4.14}$$

Commercial software packages (AVL's Advisor, Cruise, and Boost) can be used to determine η_e and η_{dt} for HDV's. A general info about software's is given in Chapter 8.

4.4 EPA 2008 FUEL ECONOMY CALCULATION METHOD[10]

As it is stated in Section 4.1, EPA 2008 fuel economy calculation is altered regarding cold start formulation in this study. Calculated fuel economy is lowered by 9.5% for both city and highway FE calculations due to non-dynamometer effects not considered.

4.4.1 City FE Calculation

City FE is calculated based on the fallowing formulae:

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[10] Federal Register, Vol. 71, No. 248, Pg. 77884

$$City\ FE = 0.905 \times \frac{1}{\left(Start\ FC + Running\ FC\right)} \tag{4.15}$$

where:

$$Start\ FC\left(\text{gallons per mile}\right) = 0.330 \times \left(\frac{0.76 \times Start\ Fuel_{75} + 0.24 \times Start\ Fuel_{20}}{4.1}\right) \tag{4.16}$$

where:

$$Start\ Fuel_x \text{ for vehicles tested over a 3-bag FTP} = 3.6 \times \left(\frac{1}{Bag\ 1\ FE_x} - \frac{1}{Bag\ 3\ FE_x}\right) \tag{4.17}$$

where: $Bag\ \mathrm{y}\ FE_{\mathrm{x}}$ is the fuel economy in miles per gallon of fuel during the specified bag of the FTP test conducted at an ambient temperature of $75^{\circ}F$ or $20^{\circ}F$.

Likewise,

$$\begin{aligned} Running\ FC = 0.82 \times & \left[\frac{0.48}{Bag\ 2\ FE_{75}} + \frac{0.41}{Bag\ 3\ FE_{75}} + \frac{0.11}{US06\ City\ FE}\right] \\ & + 0.1 \times \left[\frac{0.5}{Bag\ 2\ FE_{20}} + \frac{0.5}{Bag\ 3\ FE_{20}}\right] \\ & + 0.133 \times 1.083 \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3\ FE_{75}} + \frac{0.39}{Bag\ 2\ FE_{75}}\right)\right] \end{aligned} \tag{4.18}$$

4.4.2 Highway FE Calculation

Highway FE is calculated based on the fallowing formulae:

$$Highway\ FE = 0.905 \times \frac{1}{\left(Start\ FC + Running\ FC\right)} \tag{4.19}$$

where:

$$Start\ FC\left(\text{gallons per mile}\right) = 0.330 \times \left(\frac{0.76 \times Start\ Fuel_{75} + 0.24 \times Start\ Fuel_{20}}{60}\right) \tag{4.20}$$

and,

$$Running\ FC = 1.007 \times \left[\frac{0.79}{US06\ Highway\ FE} + \frac{0.21}{HFET\ FE} \right] + 0.133 \times 0.377 \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3\ FE_{75}} + \frac{0.39}{Bag\ 2\ FE_{75}} \right) \right] \tag{4.21}$$

4.5 RESULTS

Environmental Protection Agency (EPA) has a database of Annual Certification Tests Results at (http://www.epa.gov/otaq/crttst.htm). The Annual Certification Tests Results Report (often referred to as Federal Register Test Results Report) includes light-duty vehicle and heavy-duty engine reports for model years 1979 through 1994 and light-duty only data for later model years. The data includes target coastdown coefficients for every vehicle sold in U.S.

Years starting from 2000 till 2008 are analyzed and vehicles are classified according to the Table 4-4. After this classification, road load forces are calculated in each class for every vehicle listed in Annual Certification Test Results Database for years 2000 till 2008 to see the trend of the class and select the representative vehicles for each class.

Table 4-4 EPA Light-duty Vehicle Classification[11]

CARS		
Class	**Passenger & Cargo Volume (Cu. Ft.)**	
Two-Seaters	Any (cars designed to seat only two adults)	
Sedans		
Minicompact	< 85	
Subcompact	85 - 99	
Compact	100 - 109	
Mid-Size	110 - 119	
Large	120 or more	
Station Wagons		
Small	<130	
Mid-Size	130 - 159	
Large	160 or more	
TRUCKS		
Class	**Gross Vehicle Weight Rating (GVWR) ***	
Pickup Trucks	**Through Model Year 2007**	**Beginning Model Year 2008**
Small	< 4,500 pounds	< 6,000 pounds
Standard	4,500 - 8,500 pounds	6,000 - 8,500 pounds
Vans		
Passenger	< 8,500 pounds	
Cargo	< 8,500 pounds	
Minivans	< 8,500 pounds	
Sport Utility Vehicles (SUVs)	< 8,500 pounds	
Special Purpose Vehicles	< 8,500 pounds	

*Gross Vehicle Weight Rating (GVWR) = truck weight plus carrying capacity.

Figure 4.2 and Figure 4.3 shows the road load force F_{RL} trends for 2008 year model compact class automatic transmission and manual transmission respectively. Maximum, minimum, and average road load forces showed on these figures to see the

[11] http://www.fueleconomy.gov/FEG/info.shtml#sizeclasses

average trend in that class. If a vehicle is purely dominating the maximum road load force or minimum road load force then it is also pointed out as it is shown in Figure 4.3. A MATLAB code to generate these figures from the EPA Annual Certification Test Results Data is given in Appendix A: Road Load Force Calculation MATLAB Code.

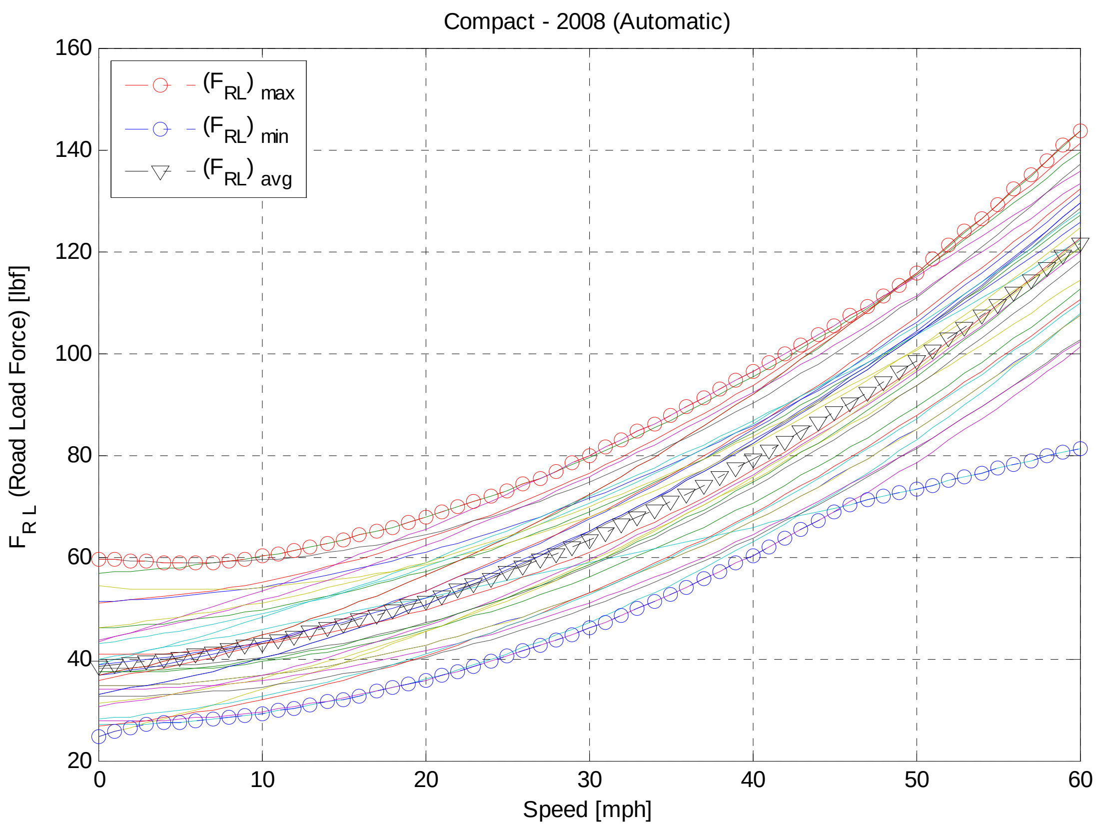


Figure 4.2 2008 Model Compact Class Road Load Force vs. Speed (Automatic Transmission)

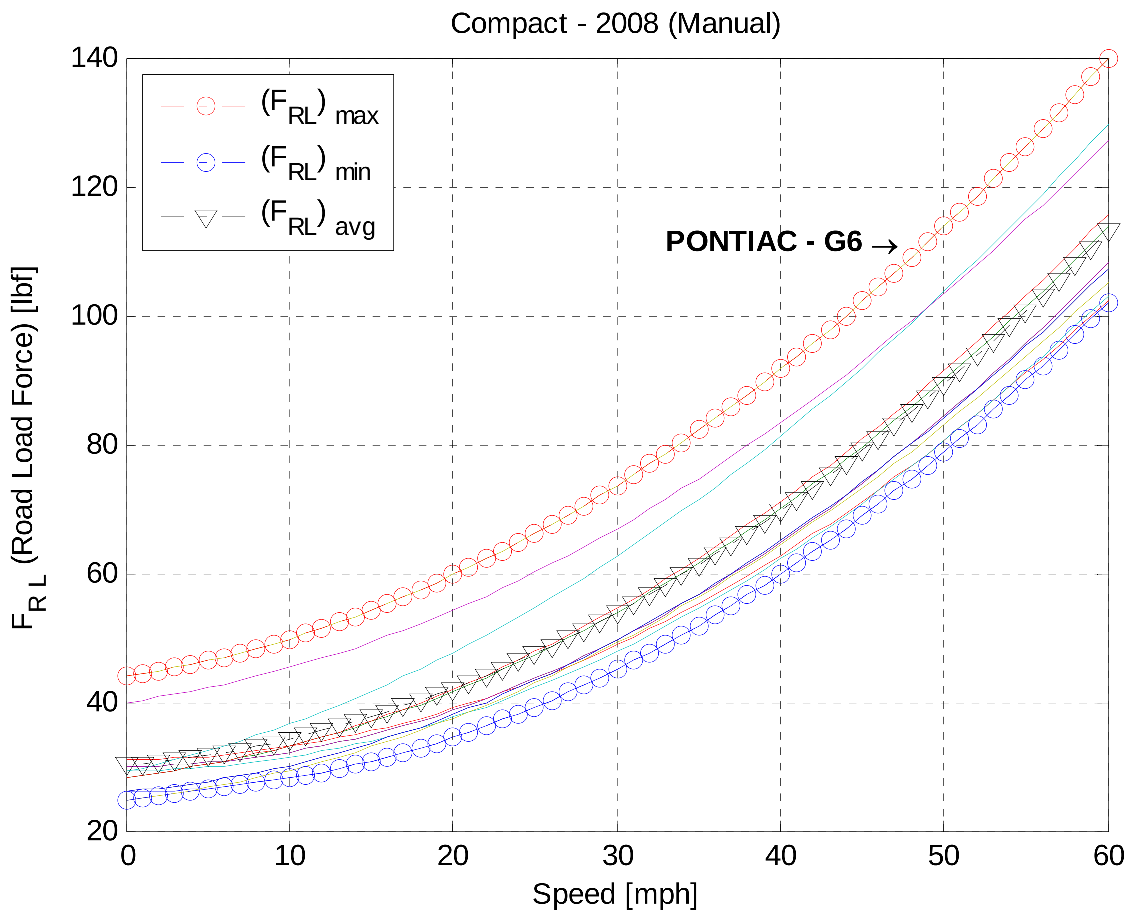


Figure 4.3 2008 Model Compact Class Road Load Force vs. Speed (Manual Transmission)

As a base calculation compact and midsize 2008 model vehicles were used, therefore for completeness of road load force comparison among these classes and their overall efficiencies following road load figures for midsize vehicles are also included.

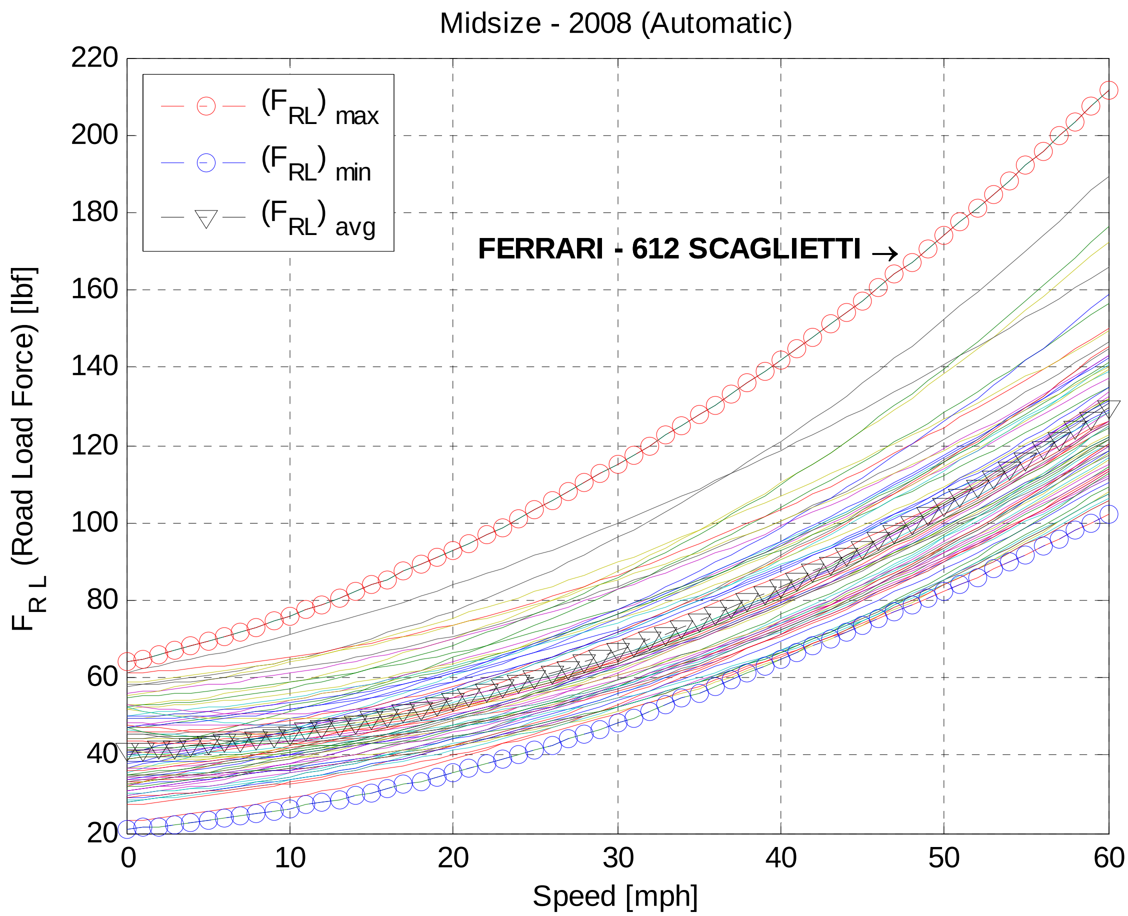


Figure 4.4 2008 Model Midsize Class Road Load Force vs. Speed (Automatic Transmission)

Sometimes due to lack of detailing in classification of light-duty vehicles, one can see extraordinary results as Ferrari 612 Scaglietti being considered as a midsize vehicle although it is well accepted as a sport car but it is not able to satisfy two-seaters class properties

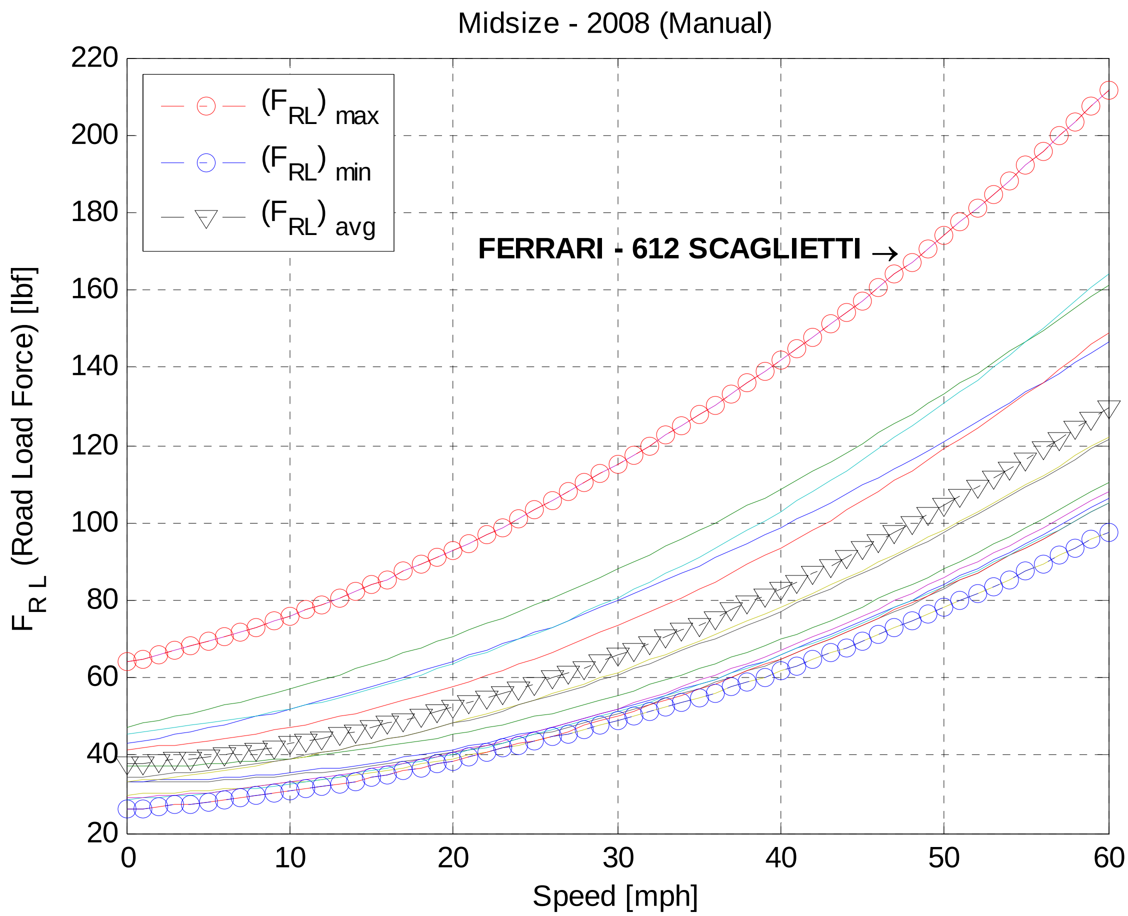
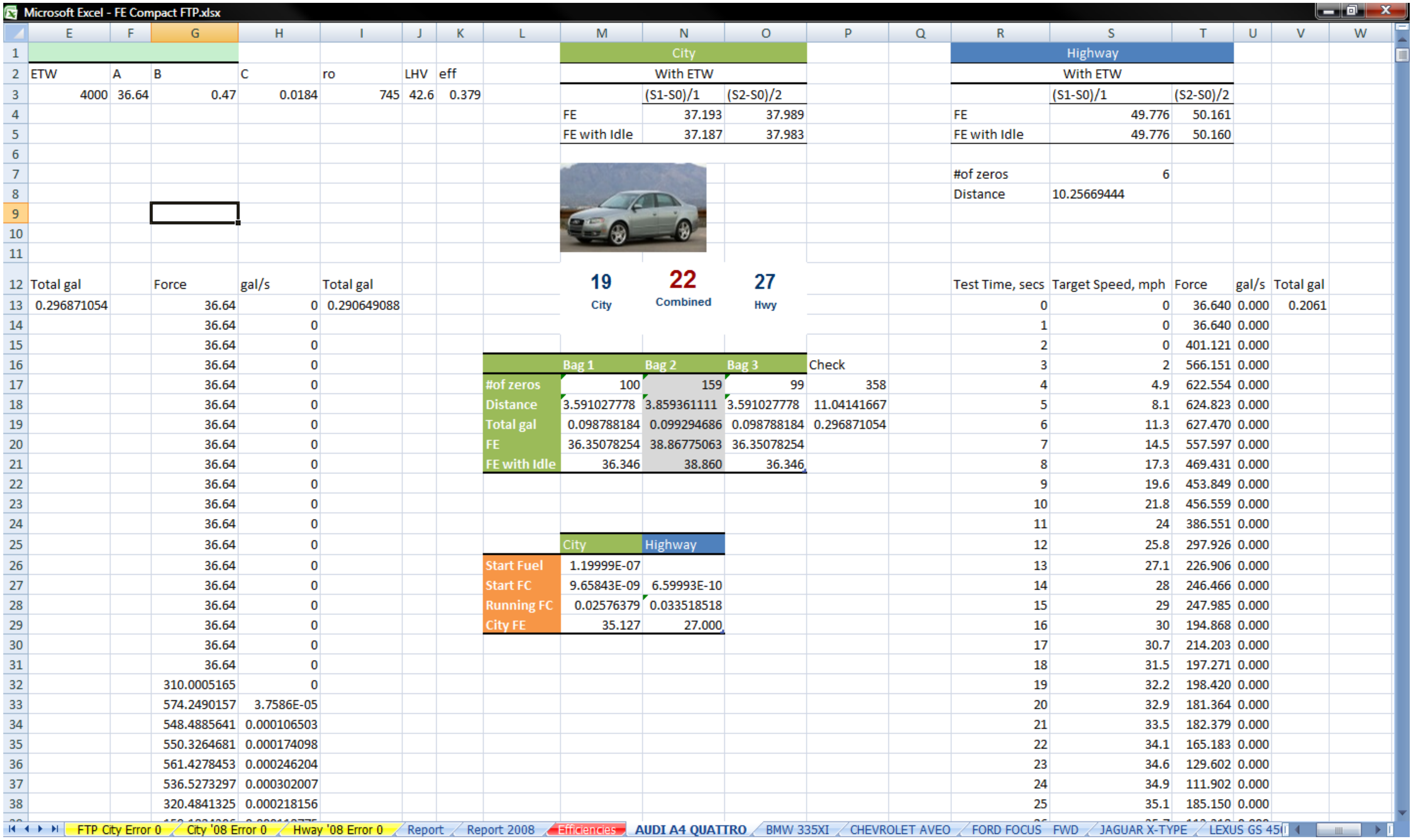


Figure 4.5 2008 Model Midsize Class Road Load Force vs. Speed (Manual Transmission)

After this analysis, class efficiencies calculated in excel sheets for selected vehicles before a whole class analysis in MATLAB. Figure 4.6 shows the Excel calculation screen of Audi A4 Quattro for city FE calculation.



Microsoft Excel - FE Compact FTP.xlsx

	E	F	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V
1									City				Highway				
2	ETW	A	B	C	ro	LHV	eff		With ETW				With ETW				
3	4000	36.64	0.47	0.0184	745	42.6	0.379			(S1-S0)/1	(S2-S0)/2			(S1-S0)/1	(S2-S0)/2		
4									FE	37.193	37.989		FE	49.776	50.161		
5									FE with Idle	37.187	37.983		FE with Idle	49.776	50.160		
6																	
7													#of zeros	6			
8													Distance	10.25669444			
9																	
10																	
11																	
12	Total gal		Force	gal/s	Total gal				19 City	22 Combined	27 Hwy		Test Time, secs	Target Speed, mph	Force	gal/s	Total gal
13	0.296871054		36.64	0	0.290649088								0	0	36.640	0.000	0.2061
14			36.64	0									1	0	36.640	0.000	
15			36.64	0									2	0	401.121	0.000	
16			36.64	0					Bag 1	Bag 2	Bag 3	Check	3	2	566.151	0.000	
17			36.64	0				#of zeros	100	159	99	358	4	4.9	622.554	0.000	
18			36.64	0				Distance	3.591027778	3.859361111	3.591027778	11.04141667	5	8.1	624.823	0.000	
19			36.64	0				Total gal	0.098788184	0.099294686	0.098788184	0.296871054	6	11.3	627.470	0.000	
20			36.64	0				FE	36.35078254	38.86775063	36.35078254		7	14.5	557.597	0.000	
21			36.64	0				FE with Idle	36.346	38.860	36.346		8	17.3	469.431	0.000	
22			36.64	0									9	19.6	453.849	0.000	
23			36.64	0									10	21.8	456.559	0.000	
24			36.64	0									11	24	386.551	0.000	
25			36.64	0					City	Highway			12	25.8	297.926	0.000	
26			36.64	0				Start Fuel	1.19999E-07				13	27.1	226.906	0.000	
27			36.64	0				Start FC	9.65843E-09	6.59993E-10			14	28	246.466	0.000	
28			36.64	0				Running FC	0.02576379	0.033518518			15	29	247.985	0.000	
29			36.64	0				City FE	35.127	27.000			16	30	194.868	0.000	
30			36.64	0									17	30.7	214.203	0.000	
31			36.64	0									18	31.5	197.271	0.000	
32			310.0005165	0									19	32.2	198.420	0.000	
33			574.2490157	3.7586E-05									20	32.9	181.364	0.000	
34			548.4885641	0.000106503									21	33.5	182.379	0.000	
35			550.3264681	0.000174098									22	34.1	165.183	0.000	
36			561.4278453	0.000246204									23	34.6	129.602	0.000	
37			536.5273297	0.000302007									24	34.9	111.902	0.000	
38			320.4841325	0.000218156									25	35.1	185.150	0.000	

FTP City Error 0 / City '08 Error 0 / Hway '08 Error 0 / Report / Report 2008 / Efficiencies / AUDI A4 QUATTRO / BMW 335XI / CHEVROLET AVEO / FORD FOCUS FWD / JAGUAR X-TYPE / LEXUS GS 45

Figure 4.6 Excel Screen of 2008 City FE Calculation

Ten vehicles from each of compact class and midsize class are selected; including cars seen daily on roads and some sport models to increase the standard deviation of the mpg calculation to increase the sensitivity of the model. Table 4-5 and Table 4-6 show the list of the vehicles in compact and midsize classes respectively.

For each vehicle five FE test mpg's are calculated by the approach explained in Section 4.3 and formulae explained in Section 4.4 are applied to calculate city and highway FE. EPA's fuel economy database for the vehicle mpg's is used to find the overall efficiency of the vehicle which is the multiplication of engine and drivetrain efficiencies.

A vehicle which runs on E85 fuel is also added to the representative vehicles, and also manual vehicles included in addition to automatic ones. The efficiencies of manual vehicles are in the range of the automatic transmission vehicles in compact and medium classes. Therefore, transmission differentiation is not needed at least for these classes for the time being but it is desirable to differentiate them. The model also proves that it can handle different types of fuels. At this point density and lower heating values at constant pressure is needed. Moreover, fuel economy calculations of hybrid vehicles are different and a four bag FTP cycle is required for them.

Table 4-5 Representative Compact Class Vehicles

Manufacturer	Carline
AUDI	A4 QUATTRO
BMW	335XI
CHEVROLET	AVEO
FORD	FOCUS FWD
JAGUAR	X-TYPE
LEXUS	GS 450H
MAZDA	MAZDA3
MERCEDES-BENZ	C300 (E85)
MERCEDES-BENZ	C300 (Premium)
MITSUBISHI	LANCER

Table 4-6 Representative Midsize Class Vehicles

Manufacturer	Carline
ACURA	RL
AUDI	S8
BMW	M5
BUICK	LACROSSE/ALLURE
CHEVROLET	MALIBU
DODGE	CALIBER
FERRARI	612
INFINITI	G35X
JAGUAR	S-TYPE R
LEXUS	ES 350

As it can be seen from the Table 4-7 and Table 4-8, calculated average efficiencies are 20.3% and 19.4% for compact class and midsize city FE's respectively. Similarly, 35.8% and 36.4% efficiencies for compact and midsize class highway FE's respectively as it is detailed in Table 4-9 and Table 4-10.

As expected at highway, midsize vehicles are more efficient than compact class where it is vice versa at city FE. 35% generic drivetrain efficiency is used to calculate highway FE and 20% generic drivetrain efficiency to calculate city FE in our model.

These generic drivetrain efficiencies are applied to whole classes and results are shown with the figures for city and highways FE's preceding the following tables.

Table 4-7 2008 Compact Class City FE Overall Drivetrain Efficiency

Manufacturer	Carline	Disp.	Transmission	Fuel	eff	City '08	City	Hwy '08	Hwy	% City Error	% Hwy Error	% eff
AUDI	A4 QUATTRO	1984	L6 LOCK-UP/AUTOMATIC/6-SPEED		0.205	19	19	15	27	0.00	45.91	0.80
BMW	335XI	2979	S6 SEMI-AUTOMATIC SIX SPEED		0.197	17	17	13	25	0.00	47.46	3.01
CHEVROLET	AVEO	1598	M5 MANUAL FIVE-SPEED		0.186	24	24	18	34	0.00	47.98	8.37
FORD	FOCUS FWD	2000	L4 LOCK-UP/AUTOMATIC/4-SPEED		0.202	24	24	18	33	0.00	45.71	0.56
JAGUAR	X-TYPE	2967	L5 LOCK-UP/AUTOMATIC/5-SPEED		0.163	16	16	14	22	0.00	36.99	19.85
LEXUS	GS 450H	3456	AV AUTOMATIC VARIABLE GEAR RATIOS		0.268	22	22	17	25	0.00	30.56	31.57
MAZDA	MAZDA3	1990	M5 MANUAL FIVE-SPEED		0.201	24	24	18	32	0.00	43.50	1.10
MERCEDES-BENZ	C300	2996	L7 LOCK-UP/AUTOMATIC/7-SPEED	E85	0.206	13	13	10	19	0.00	45.75	1.47
MERCEDES-BENZ	C300	2996	L7 LOCK-UP/AUTOMATIC/7-SPEED	Premium	0.196	18	18	14	25	0.00	43.91	3.87
MITSUBISHI	LANCER	2000	AV AUTOMATIC VARIABLE GEAR RATIOS		0.209	22	22	17	29	0.00	42.56	2.91
				avg	**0.203**	**19.900**	**19.900**	**15.363**	**27.100**	**0.000**	**43.033**	**7.350**

* Efficiencies are for which make % City Error zero.

Table 4-8 2008 Midsize Class City FE Overall Drivetrain Efficiency

Manufacturer	Carline	Disp.	Transmission	Fuel	eff	City '08	City	Hwy '08	Hwy	% City Error	% Hwy Error	% eff
ACURA	RL	3500	S5 SEMI-AUTOMATIC FIVE SPEED	11	0.190	16	16	12	24	0.00	49.68	1.96
AUDI	S8	5204	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.210	16	16	13	23	0.00	44.02	8.27
BMW	M5	4999	S7 SEMI-AUTOMATIC SEVEN SPEED	11	0.127	11	11	9	17	0.00	49.79	34.26
BUICK	LACROSSE/ALLURE	3600	L4 LOCK-UP/AUTOMATIC/4-SPEED	11	0.182	17	17	13	25	0.00	47.94	6.20
CHEVROLET	MALIBU	2400	L4 LOCK-UP/AUTOMATIC/4-SPEED	11	0.223	22	22	17	30	0.00	44.78	14.99
DODGE	CALIBER	2400	M6 MANUAL SIX SPEED	61	0.233	23	23	17	29	0.00	42.89	20.02
FERRARI	612	5748	A6 AUTOMATIC 6-SPD(NO LOCKUP)	21	0.124	9	9	7	16	0.00	59.33	36.26
INFINITI	G35X	3498	S5 SEMI-AUTOMATIC FIVE SPEED	11	0.279	17	17	13	23	0.00	42.63	43.68
JAGUAR	S-TYPE R	4196	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.174	15	15	12	22	0.00	47.30	10.21
LEXUS	ES 350	3456	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.198	19	19	15	27	0.00	44.69	1.92
				avg	**0.194**	**16.500**	**16.500**	**12.586**	**23.600**	**0.000**	**47.306**	**17.778**

* Efficiencies are for which make % City Error zero.

Table 4-9 2008 Compact Class Highway FE Overall Drivetrain Efficiency

Manufacturer	Carline	Disp.	Transmission	Fuel	eff	City '08	City	Hwy '08	Hwy	% City Error	% Hwy Error	% eff
AUDI	A4 QUATTRO	1984	L6 LOCK-UP/AUTOMATIC/6-SPEED		0.379	35	19	27	27	84.88	0.00	5.91
BMW	335XI	2979	S6 SEMI-AUTOMATIC SIX SPEED		0.376	32	17	25	25	90.33	0.00	4.92
CHEVROLET	AVEO	1598	M5 MANUAL FIVE-SPEED		0.358	46	24	34	34	92.23	0.00	0.11
FORD	FOCUS FWD	2000	L4 LOCK-UP/AUTOMATIC/4-SPEED		0.373	44	24	33	33	84.21	0.00	4.11
JAGUAR	X-TYPE	2967	L5 LOCK-UP/AUTOMATIC/5-SPEED		0.259	25	16	22	22	58.71	0.00	27.71
LEXUS	GS 450H	3456	AV AUTOMATIC VARIABLE GEAR RATIOS		0.386	32	22	25	25	44.00	0.00	7.68
MAZDA	MAZDA3	1990	M5 MANUAL FIVE-SPEED		0.356	42	24	32	32	77.00	0.00	0.51
MERCEDES-BENZ	C300	2996	L7 LOCK-UP/AUTOMATIC/7-SPEED	E85	0.381	24	13	19	19	84.32	0.00	6.29
MERCEDES-BENZ	C300	2996	L7 LOCK-UP/AUTOMATIC/7-SPEED	Premium	0.349	32	18	25	25	78.28	0.00	2.60
MITSUBISHI	LANCER	2000	AV AUTOMATIC VARIABLE GEAR RATIOS		0.365	38	22	29	29	74.09	0.00	1.81
				avg	**0.358**	**35.174**	**19.900**	**27.100**	**27.100**	**76.805**	**0.000**	**6.163**

* Efficiencies are for which make % Hway Error zero.

Table 4-10 2008 Midsize Class Highway FE Overall Drivetrain Efficiency

Manufacturer	Carline	Disp.	Transmission	Fuel	eff	City '08	City	Hwy '08	Hwy	% City Error	% Hwy Error	% eff
ACURA	RL	3500	S5 SEMI-AUTOMATIC FIVE SPEED	11	0.378	32	16	24	24	98.74	0.00	3.66
AUDI	S8	5204	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.375	29	16	23	23	78.62	0.00	2.89
BMW	M5	4999	S7 SEMI-AUTOMATIC SEVEN SPEED	11	0.254	22	11	17	17	99.15	0.00	30.35
BUICK	LACROSSE/ALLURE	3600	L4 LOCK-UP/AUTOMATIC/4-SPEED	11	0.349	33	17	25	25	92.08	0.00	4.14
CHEVROLET	MALIBU	2400	L4 LOCK-UP/AUTOMATIC/4-SPEED	11	0.404	40	22	30	30	81.10	0.00	10.79
DODGE	CALIBER	2400	M6 MANUAL SIX SPEED	61	0.407	40	23	29	29	75.11	0.00	11.82
FERRARI	612	5748	A6 AUTOMATIC 6-SPD(NO LOCKUP)	21	0.304	22	9	16	16	145.87	0.00	16.63
INFINITI	G35X	3498	S5 SEMI-AUTOMATIC FIVE SPEED	11	0.485	30	17	23	23	74.31	0.00	33.25
JAGUAR	S-TYPE R	4196	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.330	28	15	22	22	89.77	0.00	9.34
LEXUS	ES 350	3456	L6 LOCK-UP/AUTOMATIC/6-SPEED	11	0.357	34	19	27	27	80.81	0.00	1.95
				avg	**0.364**	**30.964**	**16.500**	**23.600**	**23.600**	**91.558**	**0.000**	**12.481**

* Efficiencies are for which make % Hway Error zero.

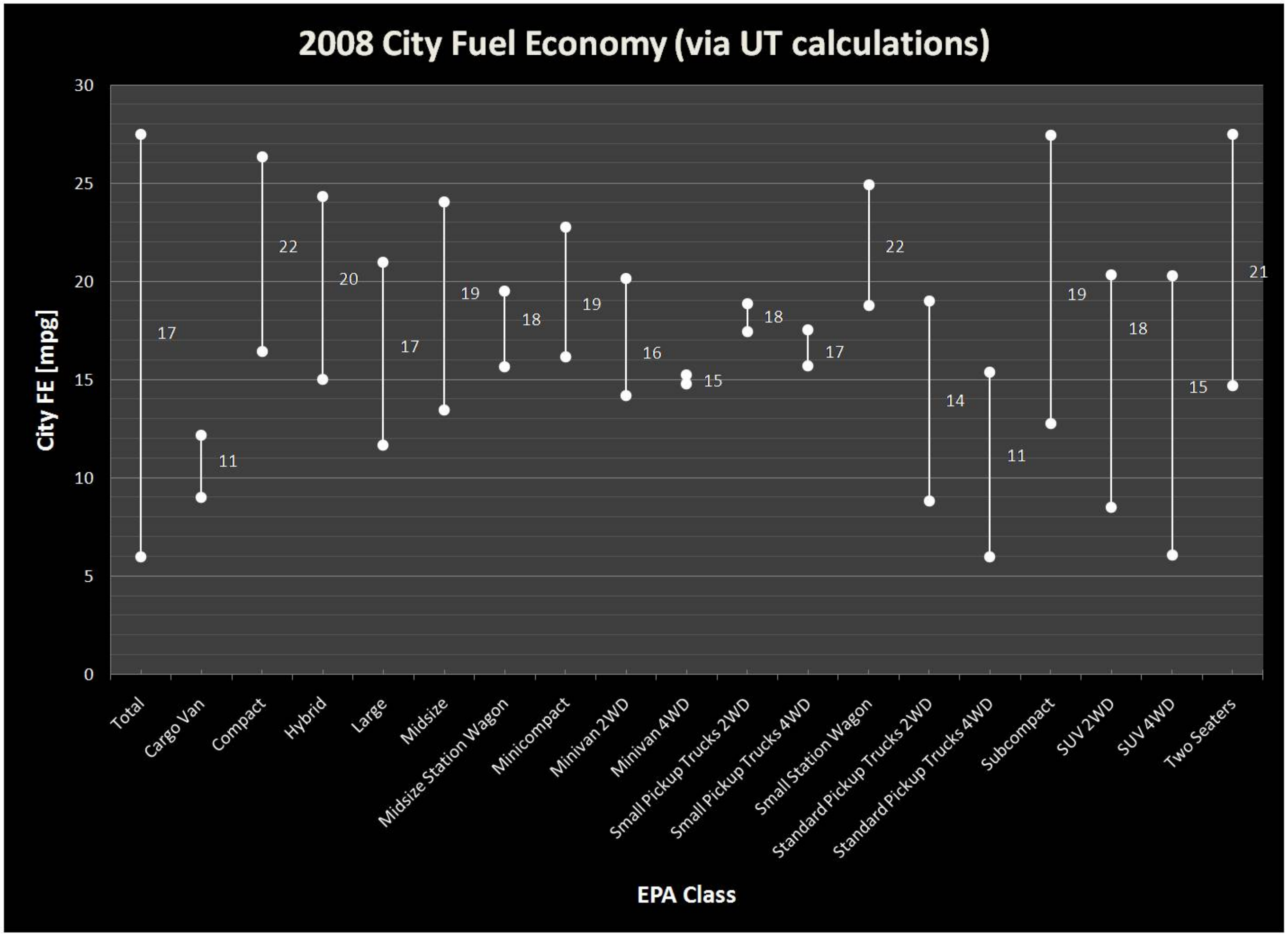


Figure 4.7 City FE Range of Vehicle Classes in Year 2008

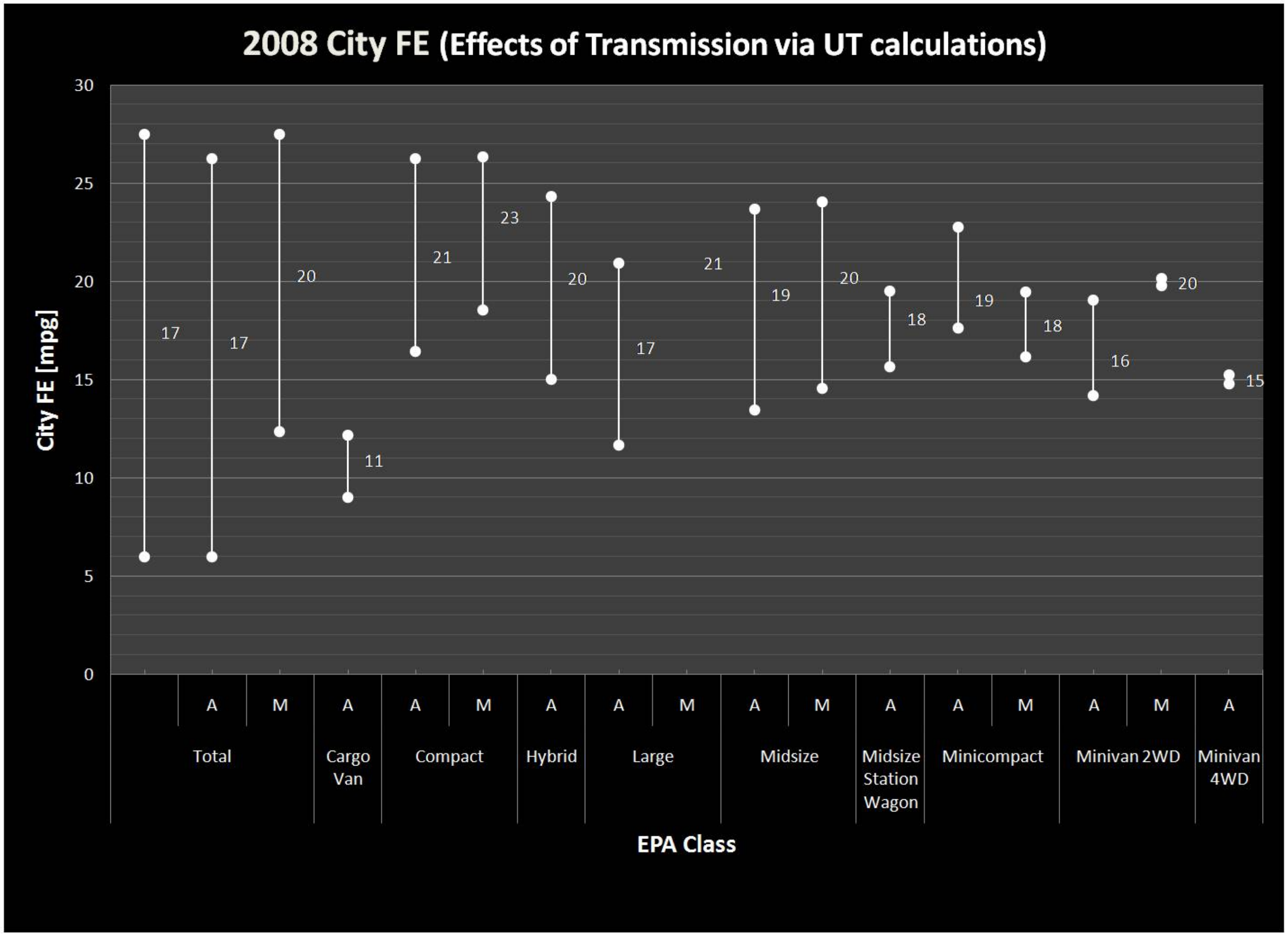


Figure 4.8 Effects of Transmission on City FE on Vehicle Class (Part 1)

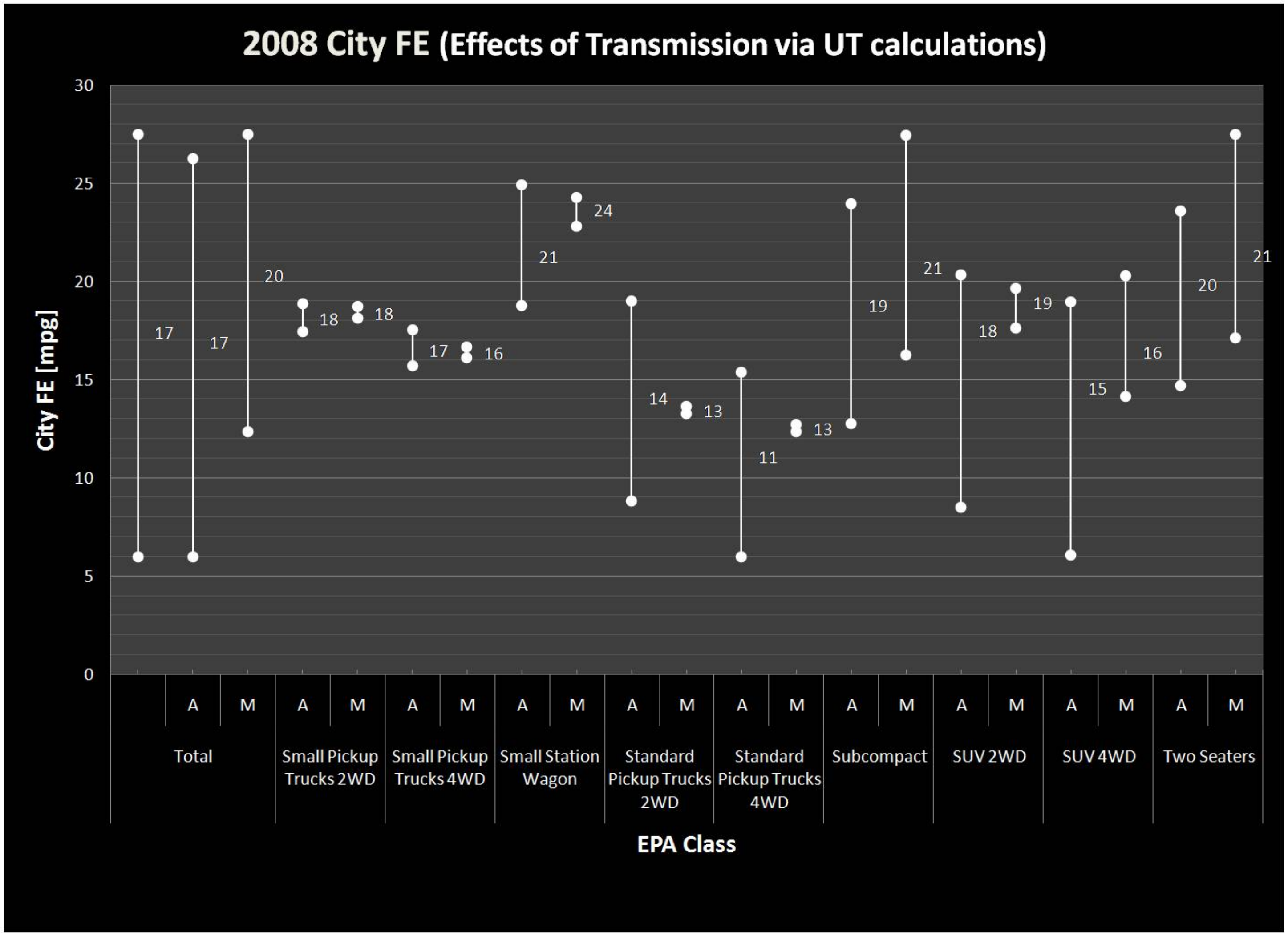


Figure 4.9 Effects of Transmission on City FE on Vehicle Class (Part 2)

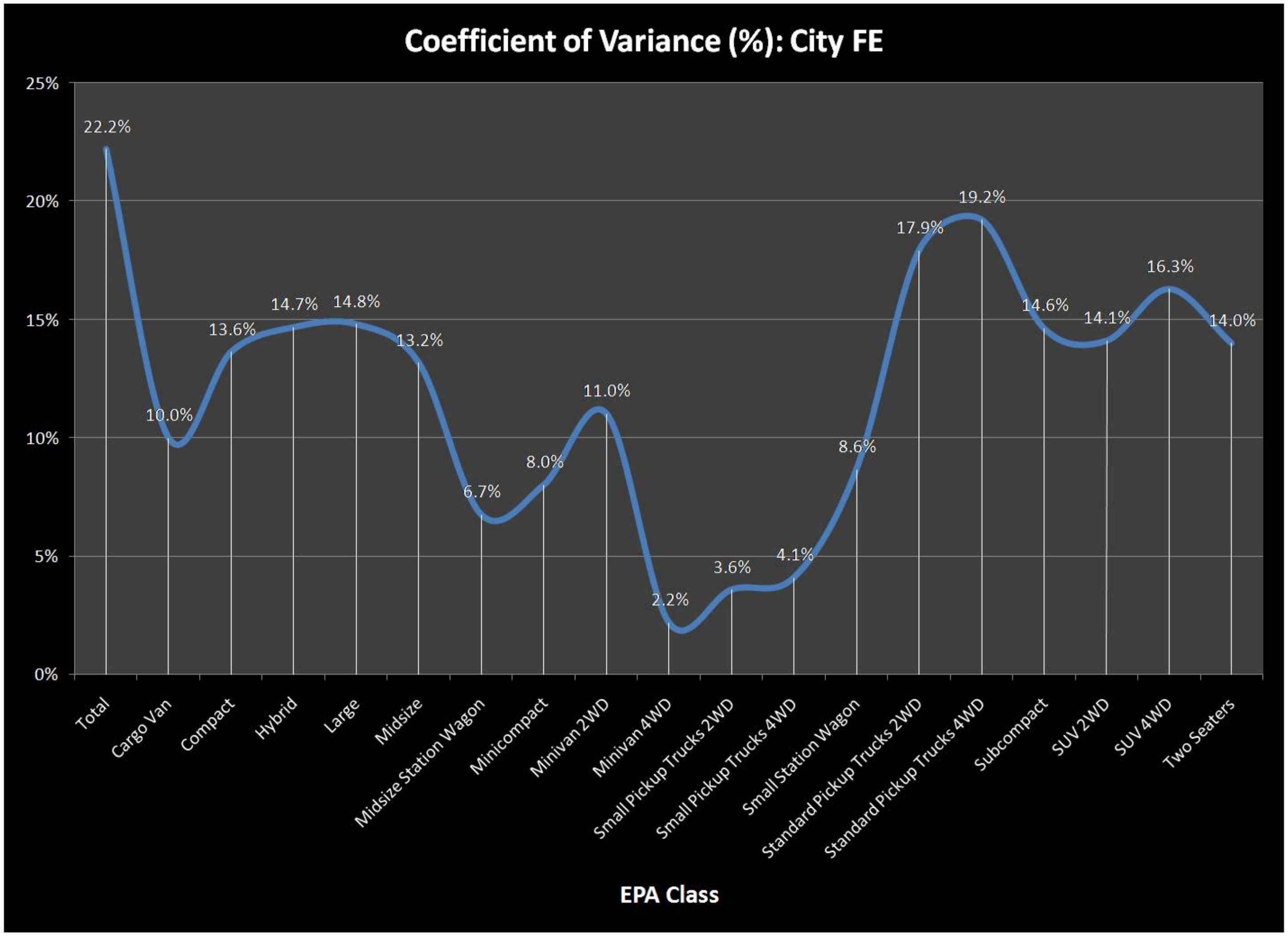


Figure 4.10 Coefficient of Variance of City FE

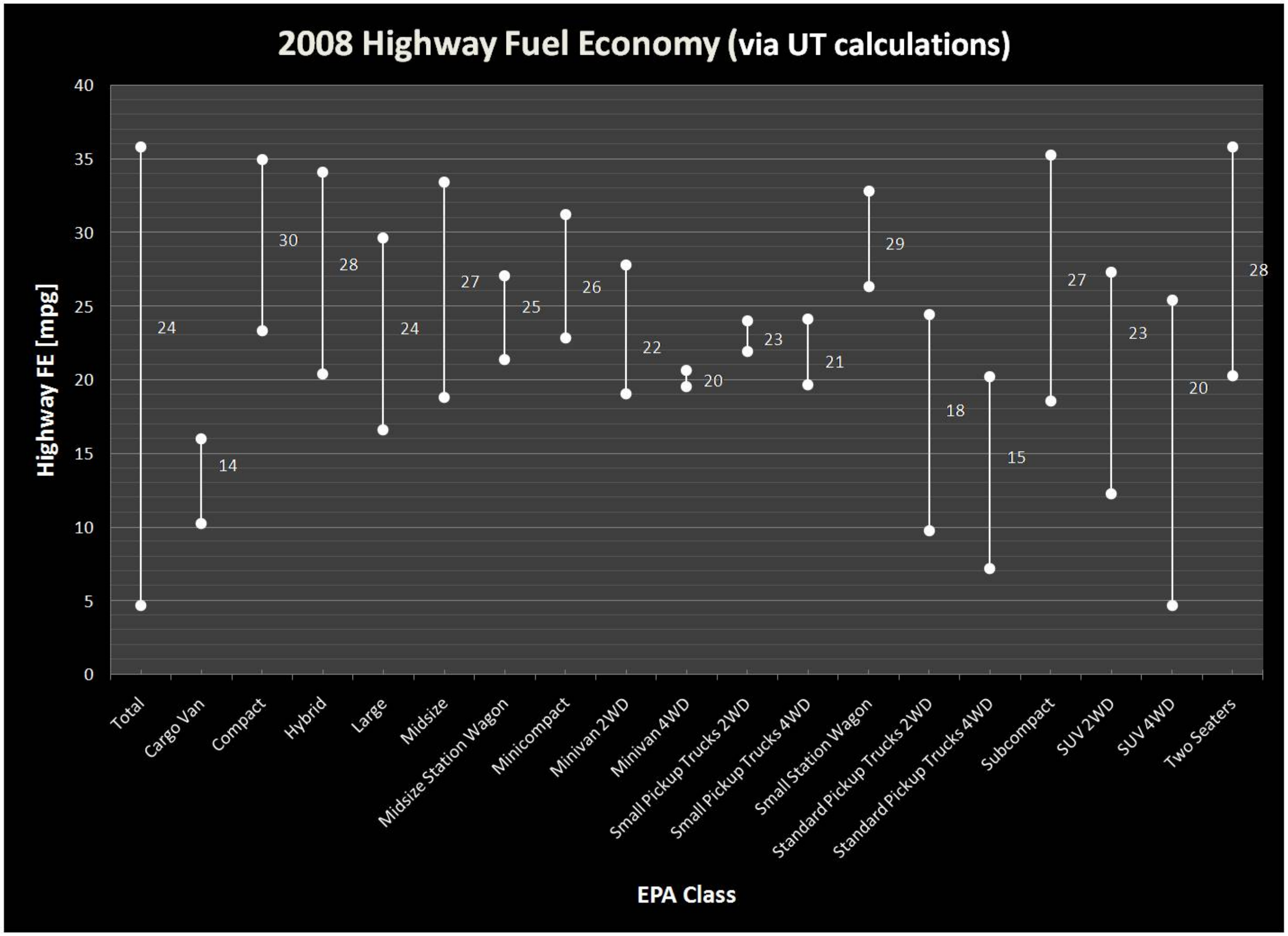


Figure 4.11 Highway FE Range of Vehicle Classes in Year 2008

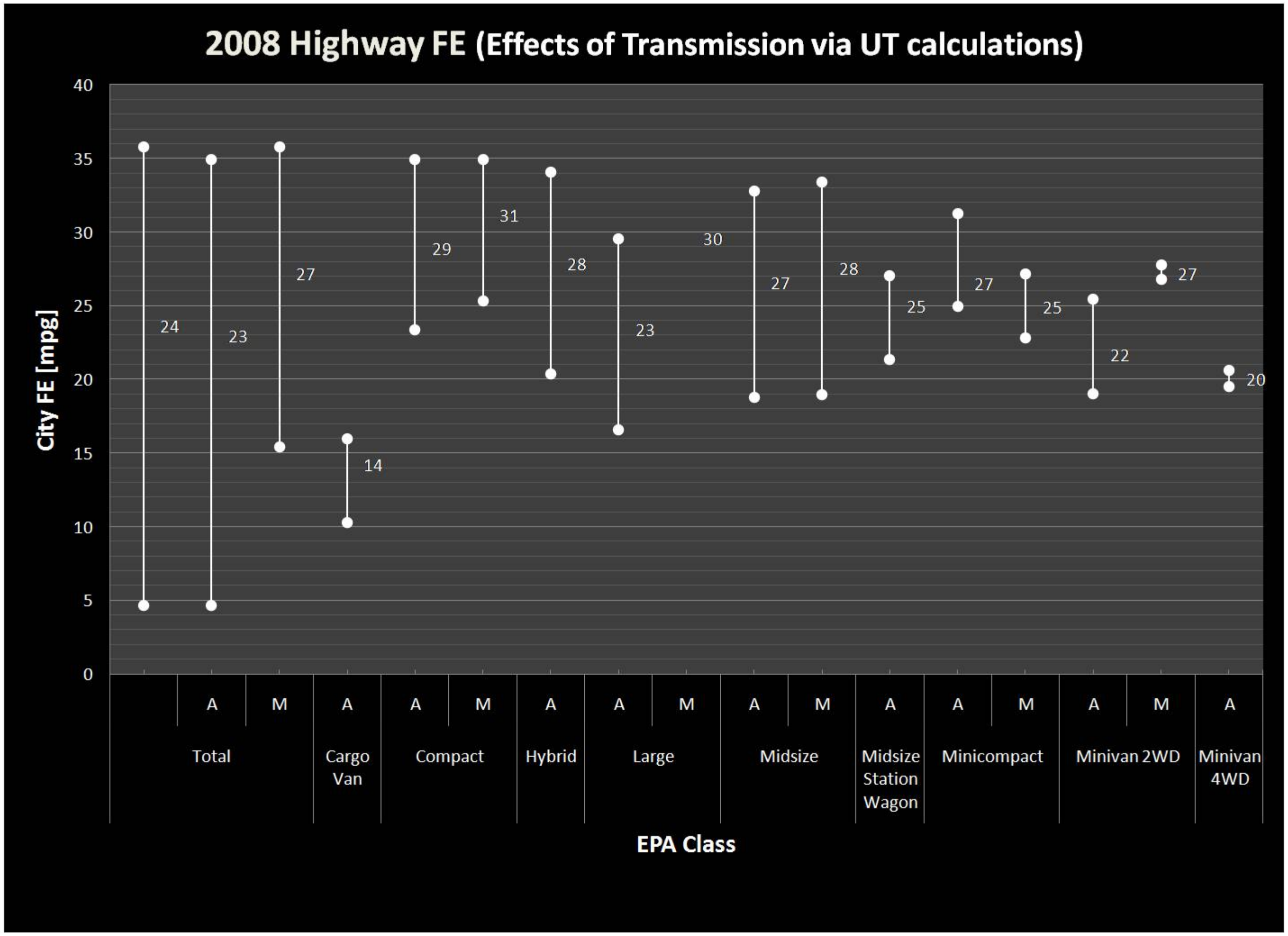


Figure 4.12 Effects of Transmission on Highway FE on Vehicle Class (Part 1)

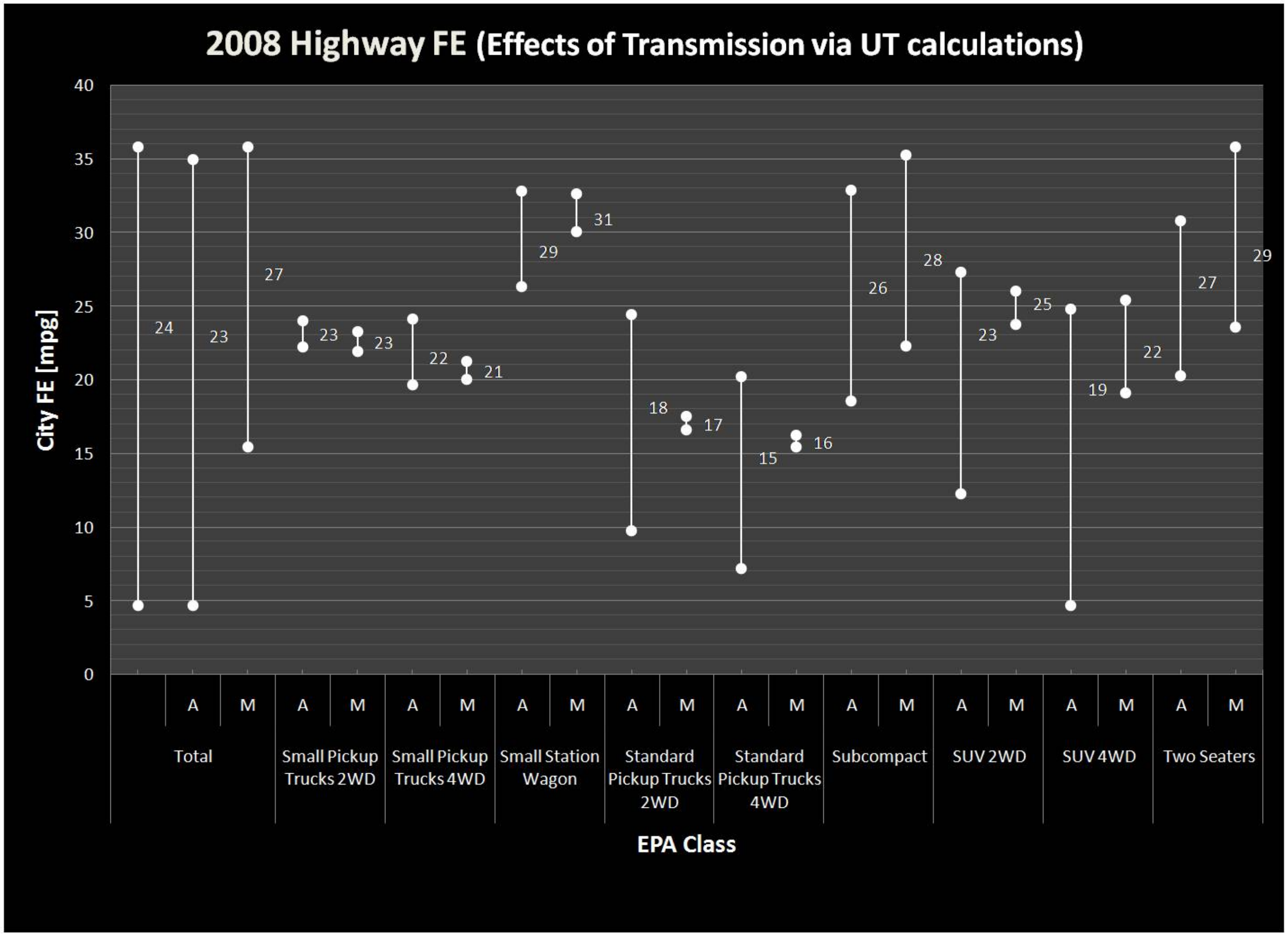


Figure 4.13 Effects of Transmission on Highway FE on Vehicle Class (Part 2)

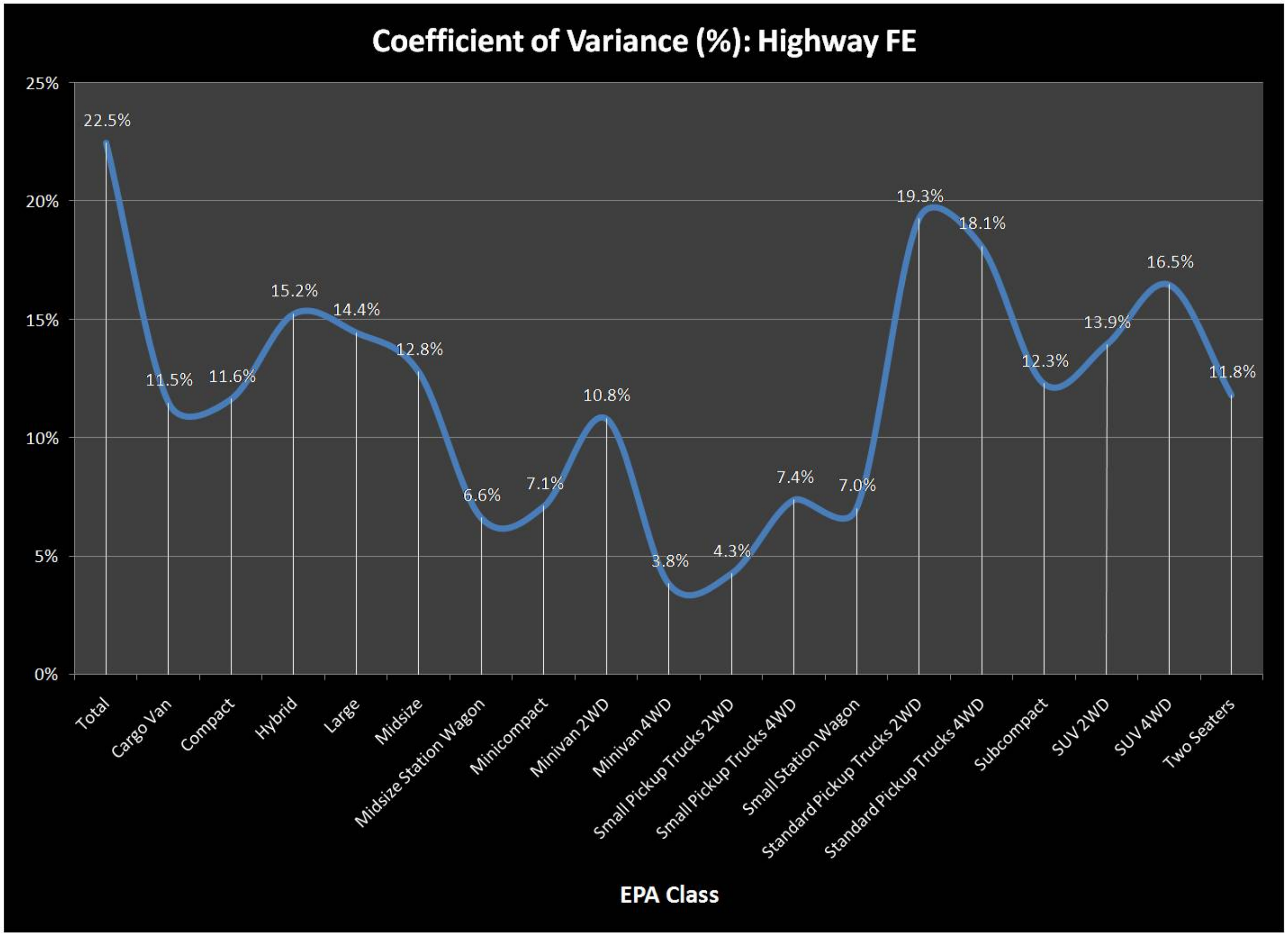


Figure 4.14 Coefficient of Variance of Highway FE

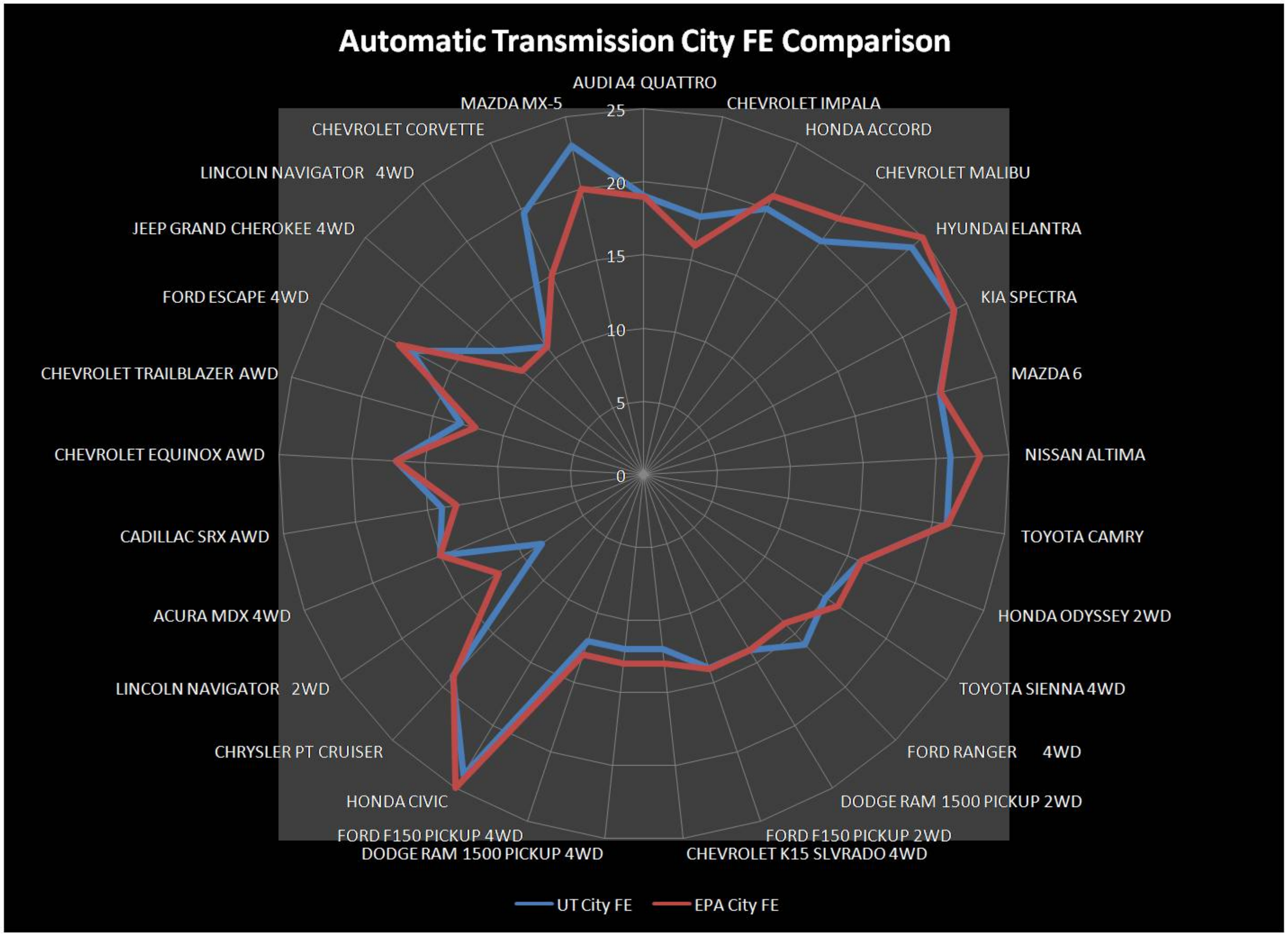


Figure 4.15 Automatic Transmission City FE Comparison of Common Vehicles on the Road

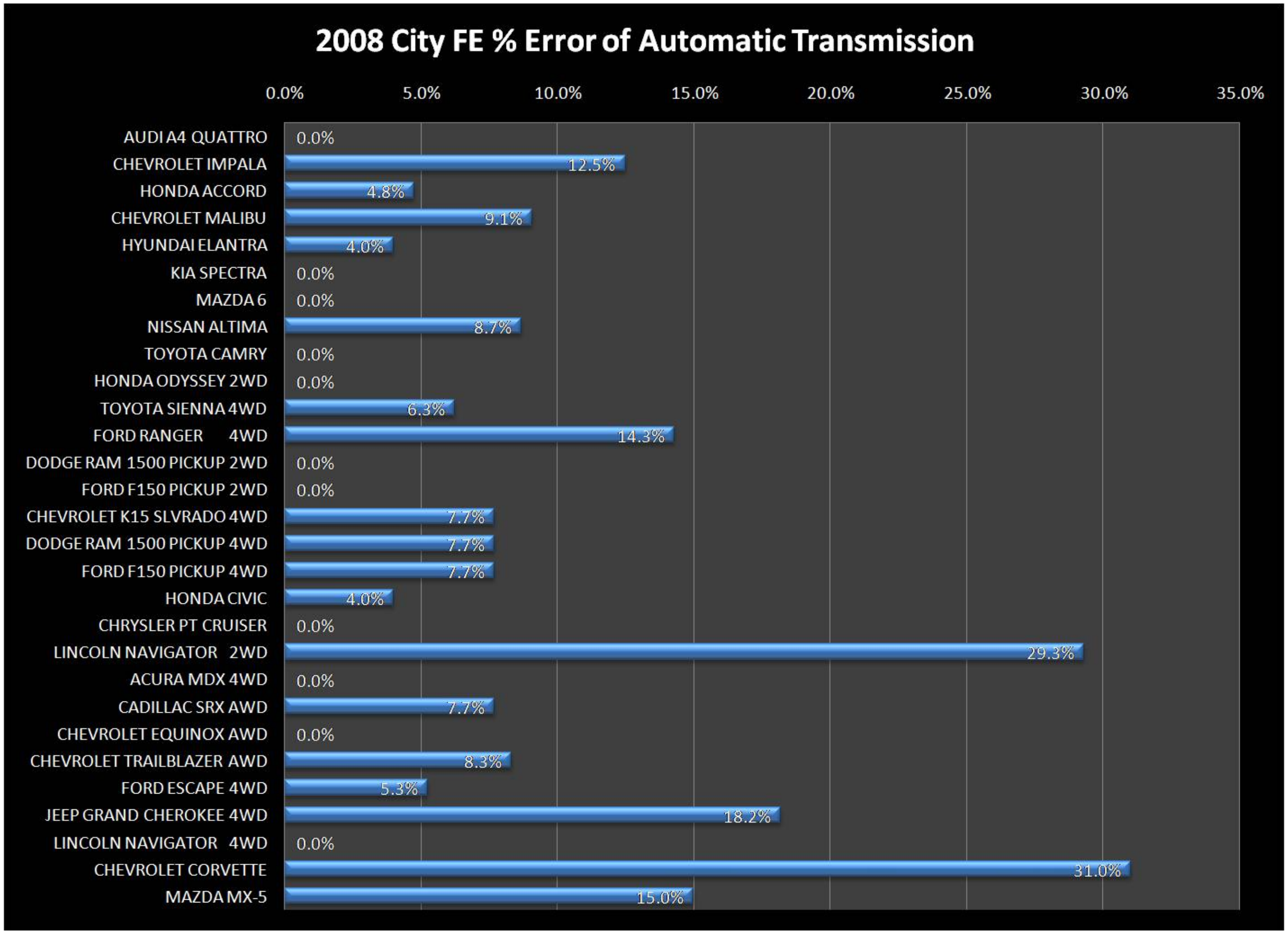


Figure 4.16 Automatic Transmission City FE % Error of Common Vehicles on the Road

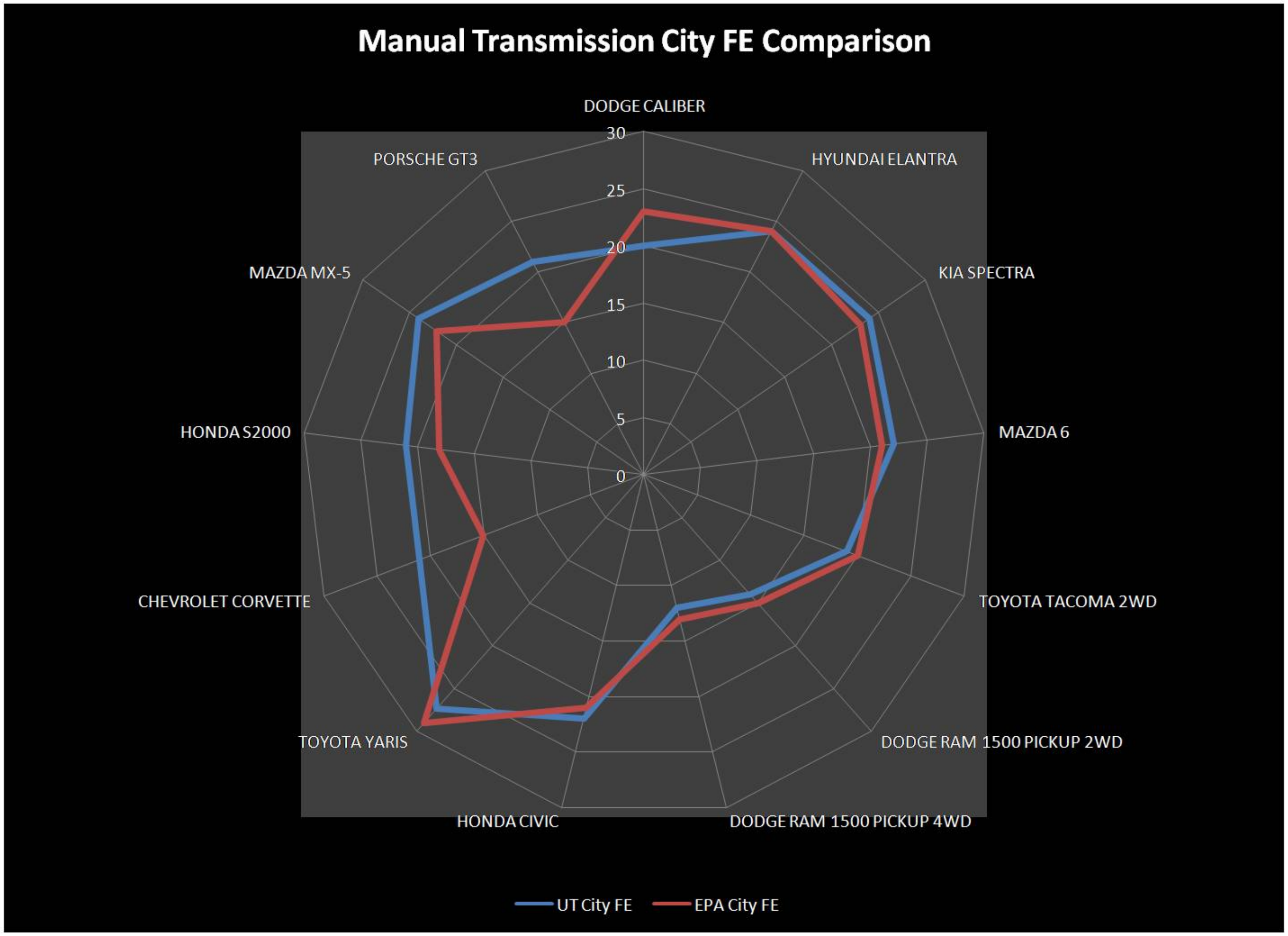


Figure 4.17 Manual Transmission City FE Comparison of Common Vehicles on the Road

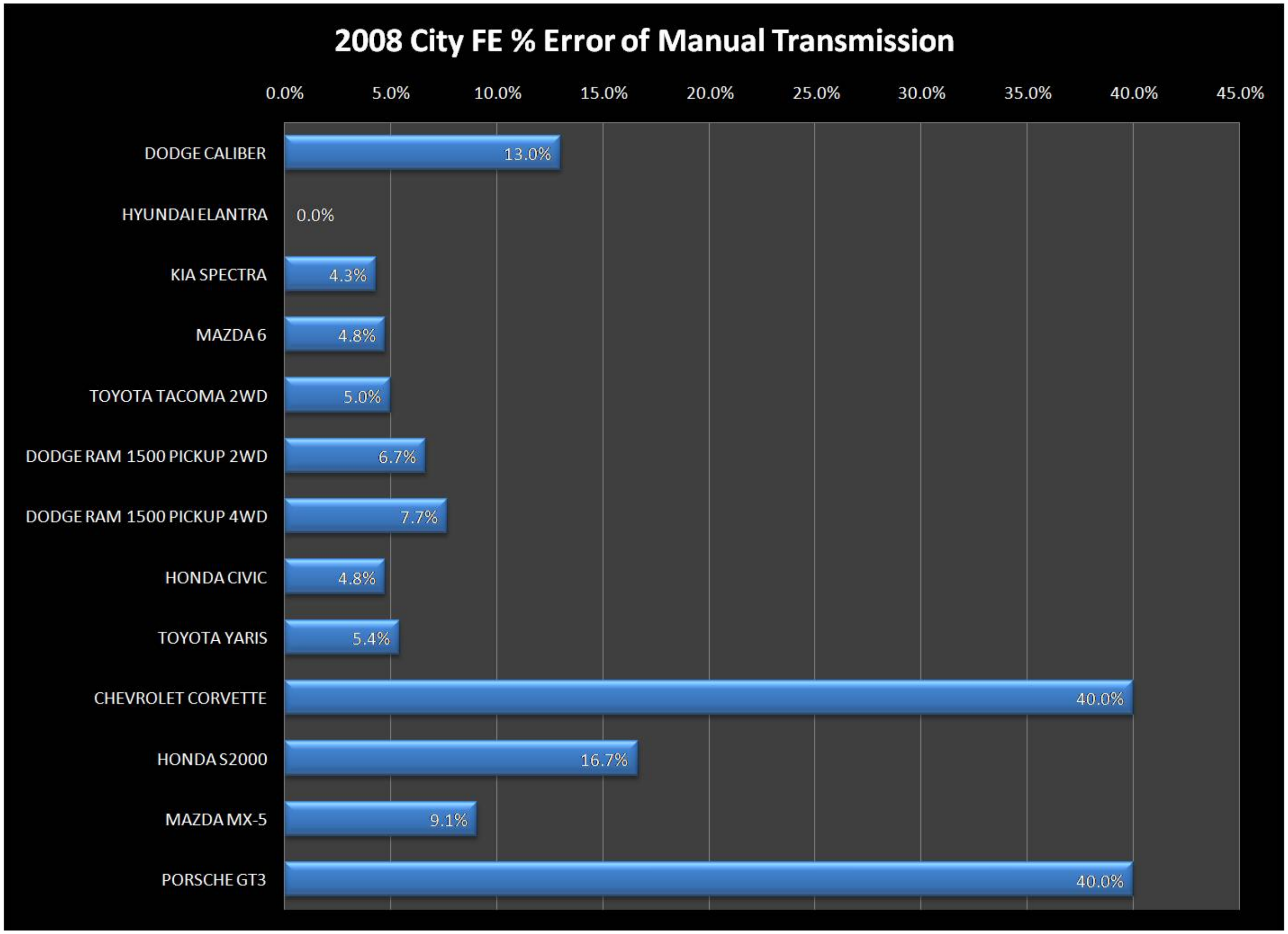


Figure 4.18 Manual Transmission City FE % Error of Common Vehicles on the Road

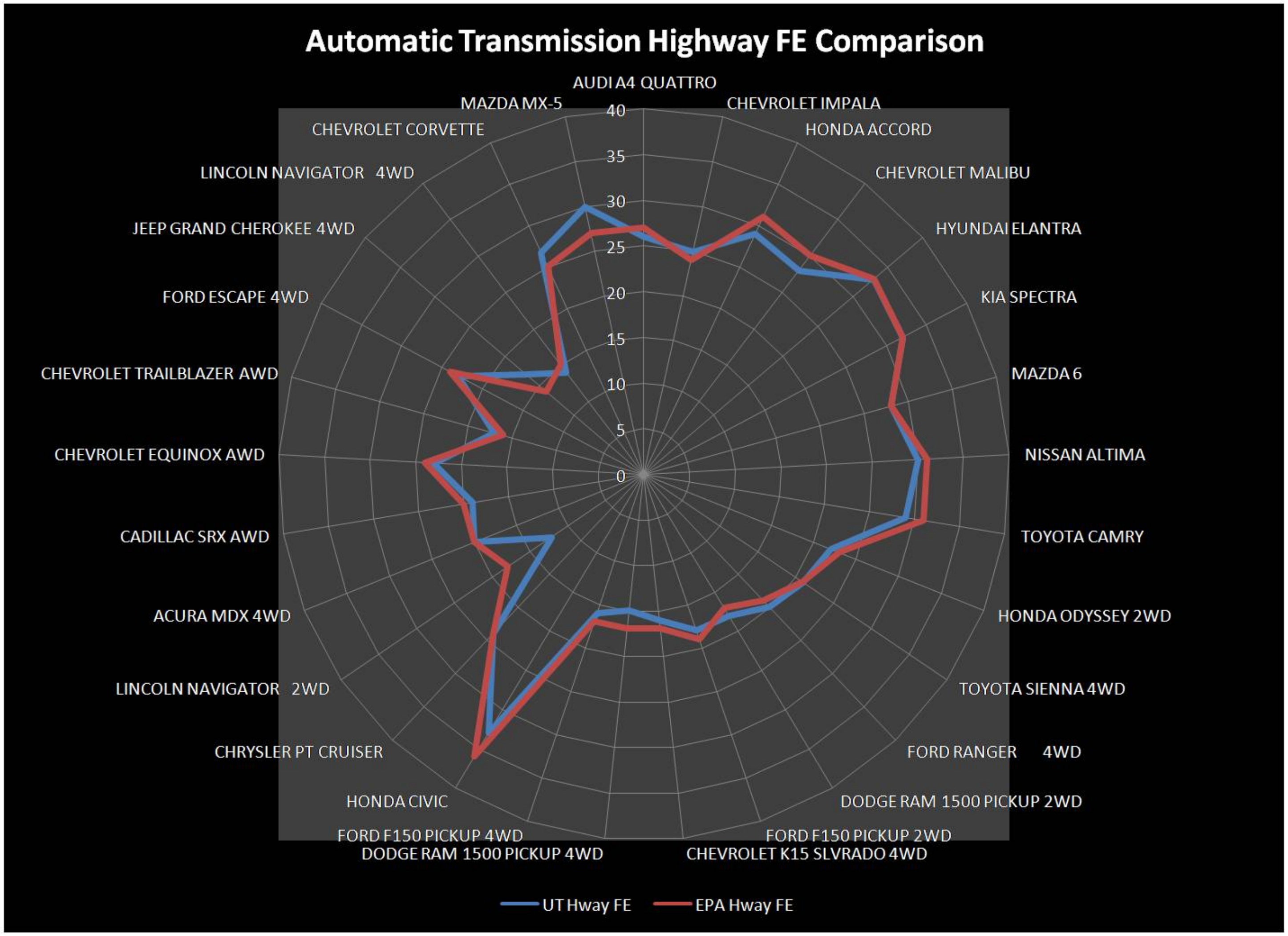


Figure 4.19 Automatic Transmission Highway FE Comparison of Common Vehicles on the Road

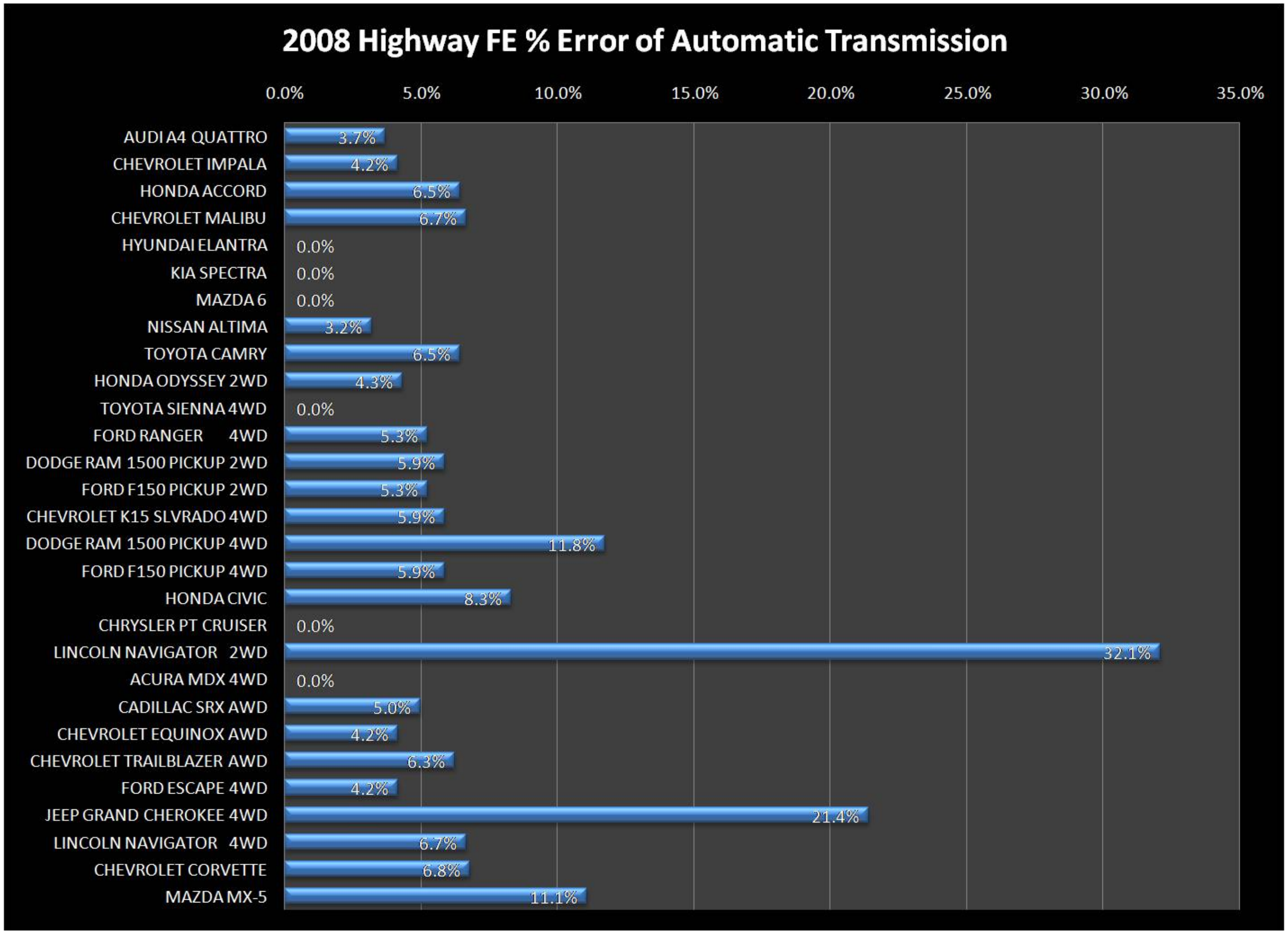


Figure 4.20 Automatic Transmission Highway FE % Error of Common Vehicles on the Road

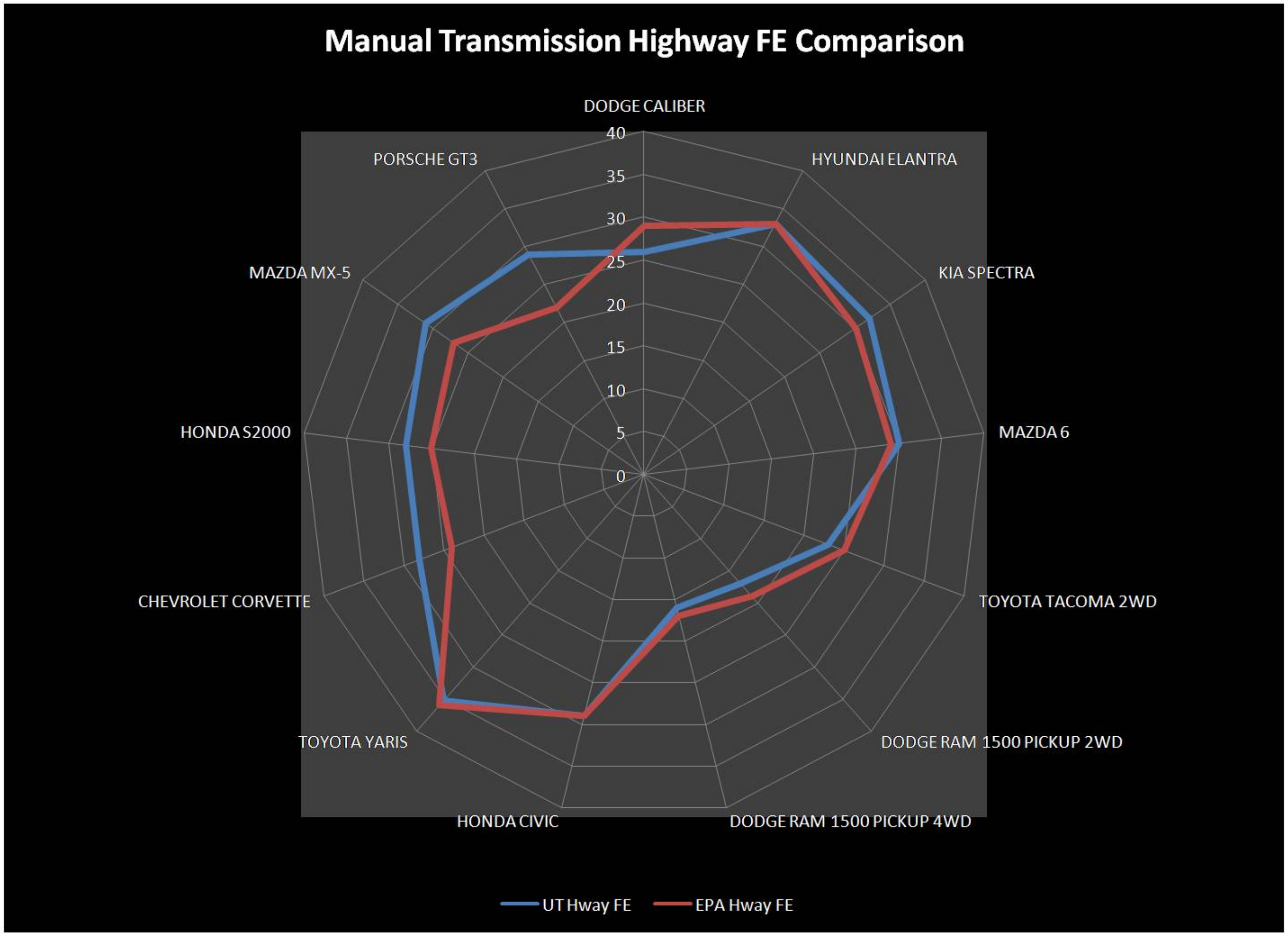


Figure 4.21 Manual Transmission Highway FE Comparison of Common Vehicles on the Road

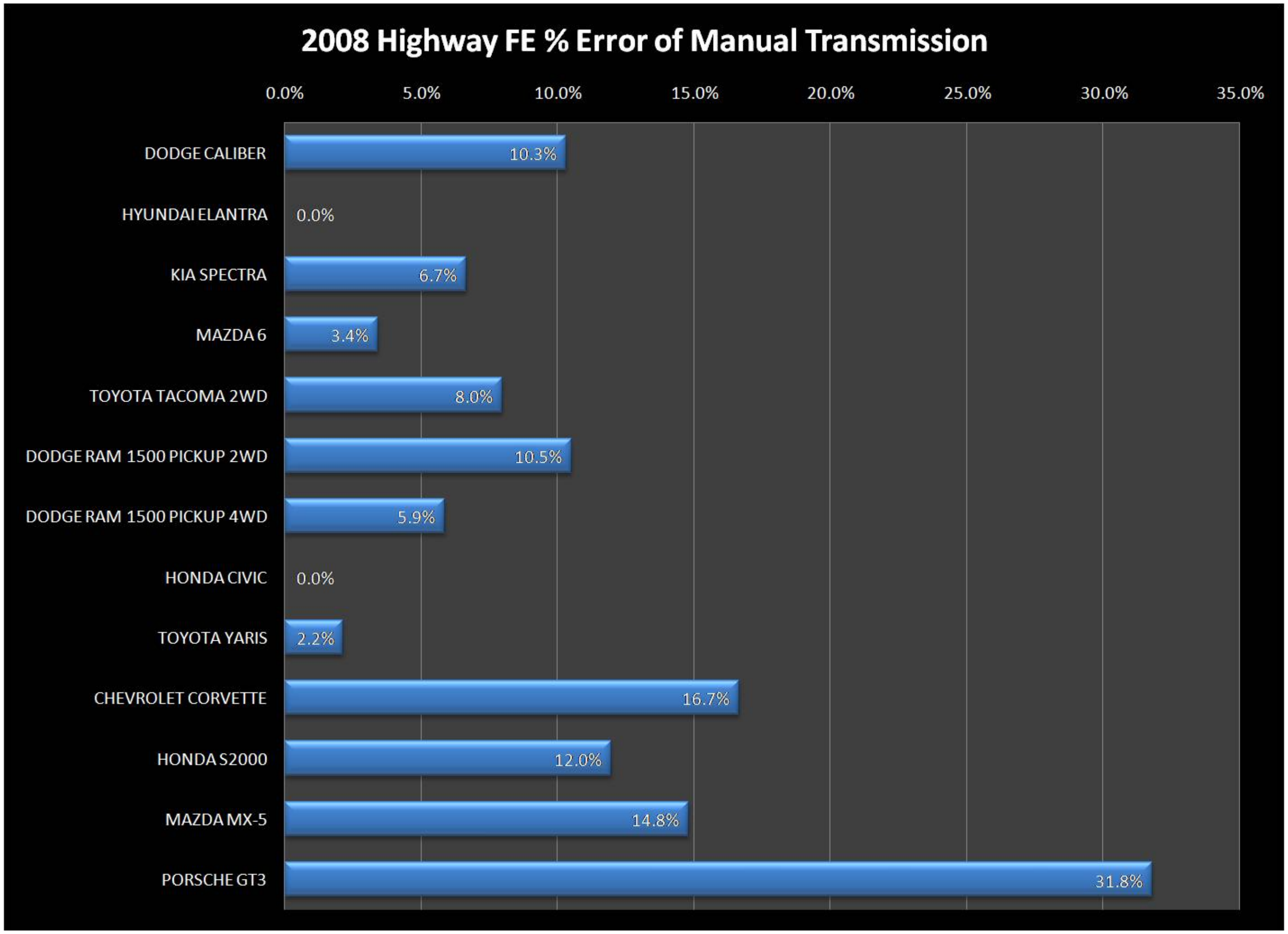


Figure 4.22 Manual Transmission Highway FE % Error of Common Vehicles on the Road

Table 4-11 Overall Drivetrain Efficiency Summary of 2008 Model Year Vehicles

	Class	2008 % City efficiency	2008 % Highway efficiency	2008 City FE [mpg]	2008 Highway FE [mpg]	% FTP efficiency	% HFET efficiency	FTP FE [mpg]	HFET FE [mpg]
Average	Compact	18.8%	34.8%	20.5	28.6	22.5%	27.0%	26.0	40.2
	Hybrid	32.9%	44.2%	35.0	36.1	41.4%	32.3%	47.0	51.2
	Large	18.8%	36.2%	15.9	23.7	22.2%	27.3%	19.8	33.1
	Midsize	19.8%	36.5%	19.9	27.6	23.6%	27.9%	25.2	38.6
	Midsize Station Wagon	19.3%	35.6%	17.1	24.1	22.8%	27.5%	21.4	33.6
	Minicompact	17.4%	32.6%	16.5	24.1	20.5%	25.1%	20.6	33.5
	Minivan 2WD	20.8%	39.7%	14.8	21.4	24.3%	30.3%	18.4	29.8
	Minivan 4WD	20.6%	36.7%	15.8	21.1	24.3%	28.1%	19.6	29.2
	Small Pickup Trucks 2WD	19.9%	36.3%	18.5	23.5	23.7%	28.7%	23.2	32.7
	Small Pickup Trucks 4WD	18.6%	33.6%	15.8	20.3	21.9%	26.9%	19.7	28.2
	Small Station Wagon	17.3%	33.0%	20.2	28.4	20.7%	26.0%	25.5	39.9
	Standard Pickup Trucks 2WD	20.1%	36.8%	14.6	19.3	23.6%	28.5%	18.2	26.7
	Standard Pickup Trucks 4WD	20.8%	38.1%	12.3	16.5	24.2%	29.3%	15.2	22.8
	Subcompact	18.1%	34.0%	17.7	25.5	21.5%	25.9%	22.3	35.7
	SUV 2WD	19.5%	36.9%	18.2	24.6	23.1%	29.0%	22.8	34.4
	SUV 4WD	21.1%	40.4%	15.8	21.0	24.9%	32.1%	19.7	29.1
	Two Seaters	15.7%	29.6%	16.8	23.4	18.6%	23.5%	21.1	32.7
	Grand	19.7%	36.5%	17.6	23.9	23.4%	28.3%	22.1	33.4

* 265 vehicles included

Table 4-11 summarizes the overall drivetrain efficiencies $\eta_{od} = \eta_e \times \eta_{dt}$ of the vehicle classes of year 2008. 265 vehicles are included to calculate these generic efficiencies. Initially it is stated that 19% generic overall drivetrain efficiency is decided for compact and midsize vehicles' city FE and 35% for highway FE. 18.8% in compact class and 19.8% midsize vehicles for city FE is calculated which is in the range of 19%. Similarly, 34.8% and 36.5% efficiencies are calculated for compact and midsize highway FE's respectively which is in the range of 35% generic overall drivetrain efficiency selected.

Chapter 5 Fuel Economy Model: A Vehicle Specific Approach

5.1 OVERVIEW

In this section a more vehicle specific analysis will be discussed instead of a class approach. It is an efficiency base calculation that includes every system that the vehicle has, starting from engine and going to the tires touching the road surface. Therefore, effects of engine parameters and drivetrain parameters on the fuel consumption can be analyzed.

5.2 ROAD LOAD FORCE MODEL

Fuel economy is mathematically expressed by Equation (4.12):

$$FE = \eta_{it}\eta_c\eta_m LHV_P \rho_f \left[\frac{\eta_t \cdot \eta_d}{F_{RL}} \right] \tag{5.1}$$

where from Equation (2.4):

$$F_{RL} = M_e \frac{dV}{dt} + A + BV + CV^2 \tag{5.2}$$

Since it is steady state driving conditions $M_e \frac{dV}{dt}$ term drops and yields:

$$F_{RL} = A + BV + CV^2 \tag{5.3}$$

5.3 COMBUSTION EFFICIENCY MODEL

For lean and stoichiometric mixtures, there is sufficient air is available to burn all of the fuel completely. Thus, assuming complete combustion:

$$\eta_c = 1.00 \text{ for } \phi \leq 1.00 \tag{5.4}$$

For rich mixtures, there is insufficient air is available to burn all of the fuel. If it is assumed that the mass of fuel burned is the portion that is in stoichiometric balance with the available oxygen:

$$\eta_c = \frac{1}{\phi} \text{ for } \phi \geq 1.00 \tag{5.5}$$

5.4 MECHANICAL EFFICIENCY MODEL

Mechanical efficiency η_m is zero when engine is idling and it increases linearly up to 25% of load and becomes constant at 0.85.

$$\begin{aligned} LOAD \geq 0.25 &\rightarrow \eta_m = 0.85 \\ LOAD \leq 0.25 &\rightarrow \eta_m = \frac{0.85}{0.25} LOAD \end{aligned} \tag{5.6}$$

where:

$$LOAD = \frac{bp_{required}}{bp} \tag{5.7}$$

and, $bp_{required}$ is the brake power required at the tires and the bp is the brake power supplied by the engine. It is known that engine rotational speed, N and the rotational speed of drive wheels, N_{dw} is not same. By using the transmission and differential gear ratios one can write:

$$N_{dw} = \frac{N}{r_t r_d} \tag{5.8}$$

where r_t is the gear ratio of the transmission and r_d is the gear ratio of the differential.

Rotational speed of the wheels can be related with vehicle speed:

$$V = N_{dw} 2\pi R_{tire} \tag{5.9}$$

where R_{tire} is the rolling radius of the tires.

$$D_{tire}(inch) = \frac{2Section\ width \times Aspect\ ratio}{2540} + Wheel\ diameter \tag{5.10}$$

By combining Equations (5.8) and (5.9):

$$\frac{V}{2\pi R_{tire}} = \frac{N}{r_t r_d} \tag{5.11}$$

Rearrange:

$$N = \frac{V r_t r_d}{2\pi R_{tire}} = \frac{V r_t r_d}{\pi D_{tire}} \tag{5.12}$$

Brake power that is available at the engine crankshaft can be calculated by assuming a linear relationship between idle engine operating condition and wide open throttle condition where maximum brake power of the engine is attained:

$$bp = N \times slope + constant \tag{5.13}$$

where:

$$slope = \frac{bp_{max} - bp_{idle}}{N_{bp_{max}} - N_{bp_{idle}}} \tag{5.14}$$

and,

$$constant = bp_{max} - slope \times N_{bp_{max}} \tag{5.15}$$

Idle brake power can be calculated by using Equation (3.48):

$$bp_{idle} = [\eta_{it}\eta_v]\eta_c\eta_m\rho_a D\left(\frac{N_{idle}}{x}\right)\phi FA_s LHV_P \tag{5.16}$$

Mechanical efficiency is assumed to be 0.85 in idle operation and only unknown term is the multiplication of the indicated thermal efficiency and volumetric efficiency and they assumed to be almost constant during operation of the engine and can be derived from the wide open throttle position state:

$$[\eta_{it}\eta_v] = \frac{bp_{max}}{\eta_c\eta_m\rho_a D\left(\frac{N_{bp_{max}}}{x}\right)\phi FA_s LHV_P} \tag{5.17}$$

Therefore, brake power at any engine speed can be calculated at the Equation (5.7) to calculate $LOAD$. Only portion left in that equation is the $bp_{required}$. From Equation (4.10) brake power can be written as:

$$bp_{required} = \frac{VF_{RL}}{\eta_t \cdot \eta_d} \tag{5.18}$$

Equation (5.18) completes the load calculation and therefore determination of the mechanical efficiency.

It is well known that transmission efficiencies η_t for each gear ratio can be assumed to be constant. An example of η_t for a four speed automatic transmission can be given as:

Table 5-1 Example Transmission Gear Efficiencies

Gear	η_t
1	0.85
2	0.87
3	0.88
4	0.90

Differential efficiency η_d can be calculated by:

$$\begin{aligned} &if \;\; V < 150 \;\; {}^{km}\!/\!_{hr} \\ &\eta_d = 0.6652 + 0.003732V - 0.00001061V^2 \\ &else \\ &\eta_d = 0.987 \end{aligned} \tag{5.19}$$

A speed changing strategy is needed for calculation of the engine speed and other related parameters:

Table 5-2 Gear Shifting Strategy

Speed	Gear
< 20	1
< 40	2
< 60	3
≥ 60	4

5.5 Indicated Thermal Efficiency Model

The only parameter left is the indicated thermal efficiency η_{it} in the calculation of fuel economy by Equation (5.1). η_{it} can be modeled in different ways starting from the most basic method to the most advanced form it will be described in the following paragraphs.

The well known Air Standard Otto cycle treats the combustion process as a heat addition at constant volume and η_{it} can be expressed as:

$$\eta_{it} = 1 - \frac{1}{r_c^{k-1}} \tag{5.20}$$

where r_c is the compression ratio and k is the ratio of the specific heats of the air. Since Equation (5.20) overestimates the indicated thermal efficiency by factor of 2 it is multiplied by $1/2$ to get a better estimation.

$$\eta_{it} = \frac{1}{2}\left(1 - \frac{1}{r_c^{k-1}}\right) \tag{5.21}$$

Equation (5.21) models indicated thermal efficiency for maximum engine speed but efficiency drops to around 40% of this maximum indicated thermal efficiency for idle engine speed. Figure 5.1 shows a linear trend of indicated thermal efficiency changing with engine speed. A better estimation can be a quadratic fit between maximum indicated efficiency and 40% of that value. For a quadratic fit one needs another point and that can be the 83% of the maximum indicated thermal efficiency at engine speed of $\left(\frac{N_{idle} + N_{max}}{2}\right)$.

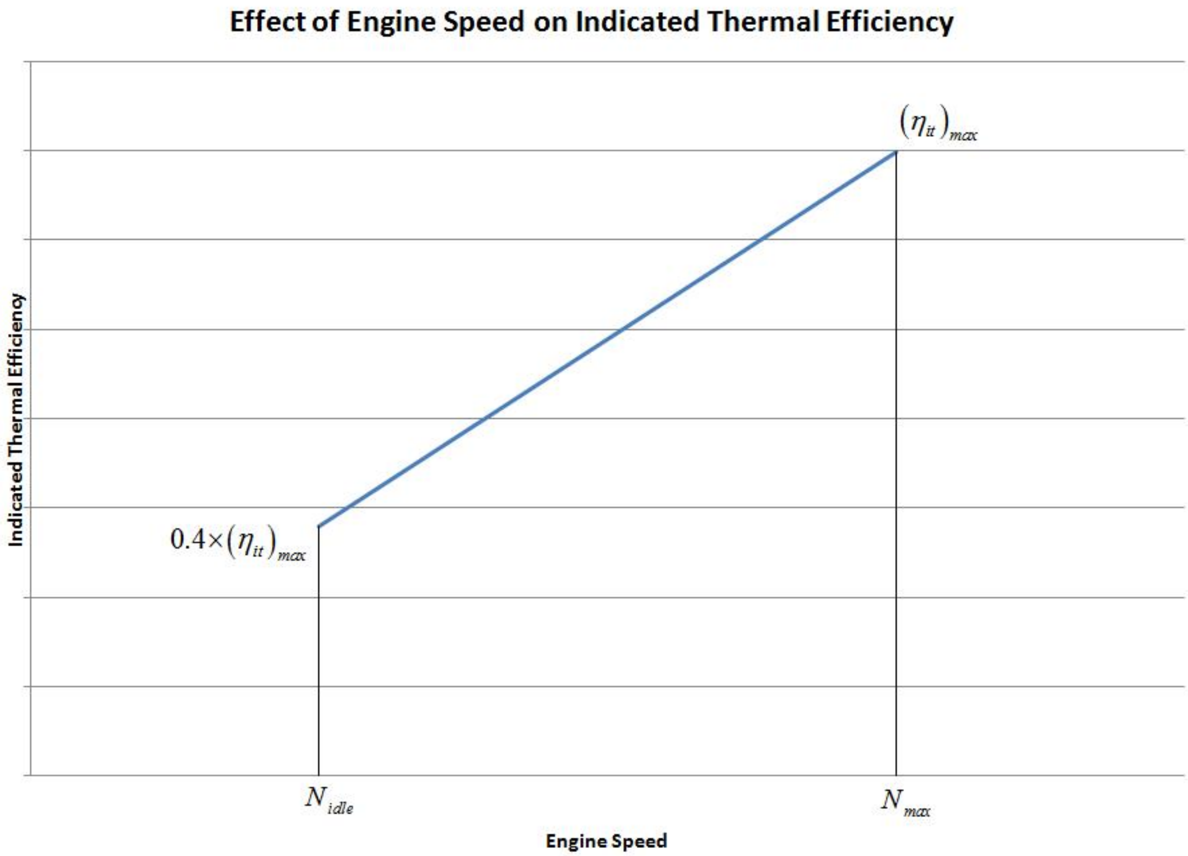


Figure 5.1 Effect of Engine Speed on Indicated Thermal Efficiency

5.5.1 Air Equivalent SI Engine Model

A better estimation for indicated thermal efficiency can be obtained via Air Equivalent SI Engine Model (AESI). Homogenous charge 4-stroke SI engine is the most commonly used engine in the world, and in fact this engine dominates the market by a significant margin. Therefore analysis will focus on homogenous charge 4-stroke SI engine exclusively.

Assumptions:[12]

1) Variable specific heat of air is assumed.
2) The intake and exhaust strokes are included in the cycle analysis.
3) It is assumed that exhaust stroke is reversible and isobaric.
4) It is assumed that no heat transfer occurs within the cylinder during the intake and exhaust processes. It will be also assumed that the valves open and close instantaneously at TDC and BDC and there are no pressure losses associated with flow across the valves. Also it is assumed that there is not any pressure losses associated with the flow through inlet manifold and exhaust system.
5) The working fluid has the properties of air, but displacement of the air by the fuel and residual gases is taken into account.
6) The compression, heat addition, expansion, and exhaust blowdown processes are idealized.

Figure 5.2 shows a typical cross section of a SI engine cylinder. More information will be given in the following paragraphs about SI strokes and the $P-v$ diagrams of the AESI model.

[12] R. D. Matthews, 2007

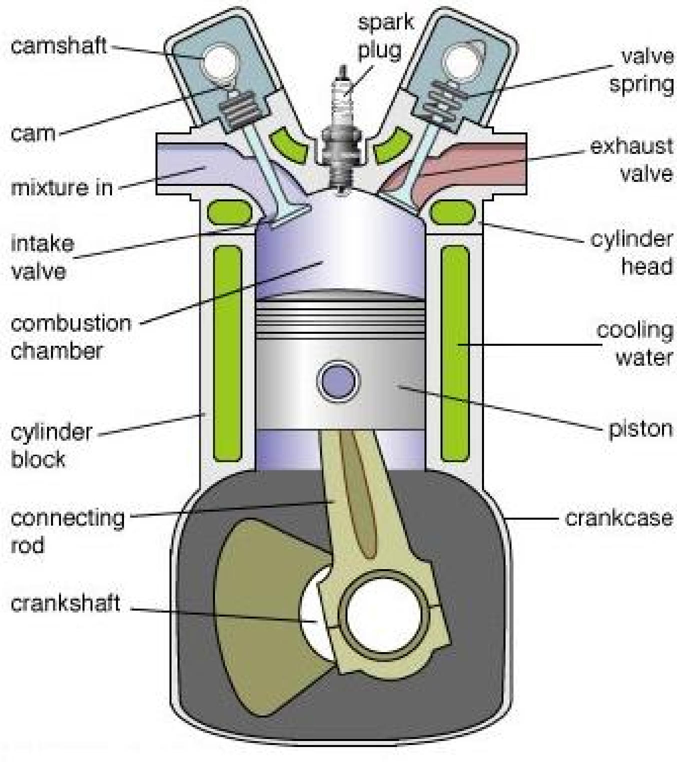


Figure 5.2 Cross Section Showing One Cylinder of a Four-stroke Internal Combustion Engine.[13]

Figure 5.3 shows the four-stroke of the SI engine schematically. Air and fuel mixture enters the cylinder in the inlet stroke through the open inlet valves as the piston travels downward and creating a sucking force. In the compression stroke inlet valve closes and the piston travels upwards compressing the air fuel mixture and increasing its temperature. By spark plug mixture of air and fuel is ignited and the mixture starts to combust. The pressure increase forces the piston downwards providing power and this stroke is called the power stroke. And finally, products of the combustion and any

[13] Merriam-Webster

remaining unburned or partially burned fuel are pushed out of the open exhaust valves by the moving piston upwards.

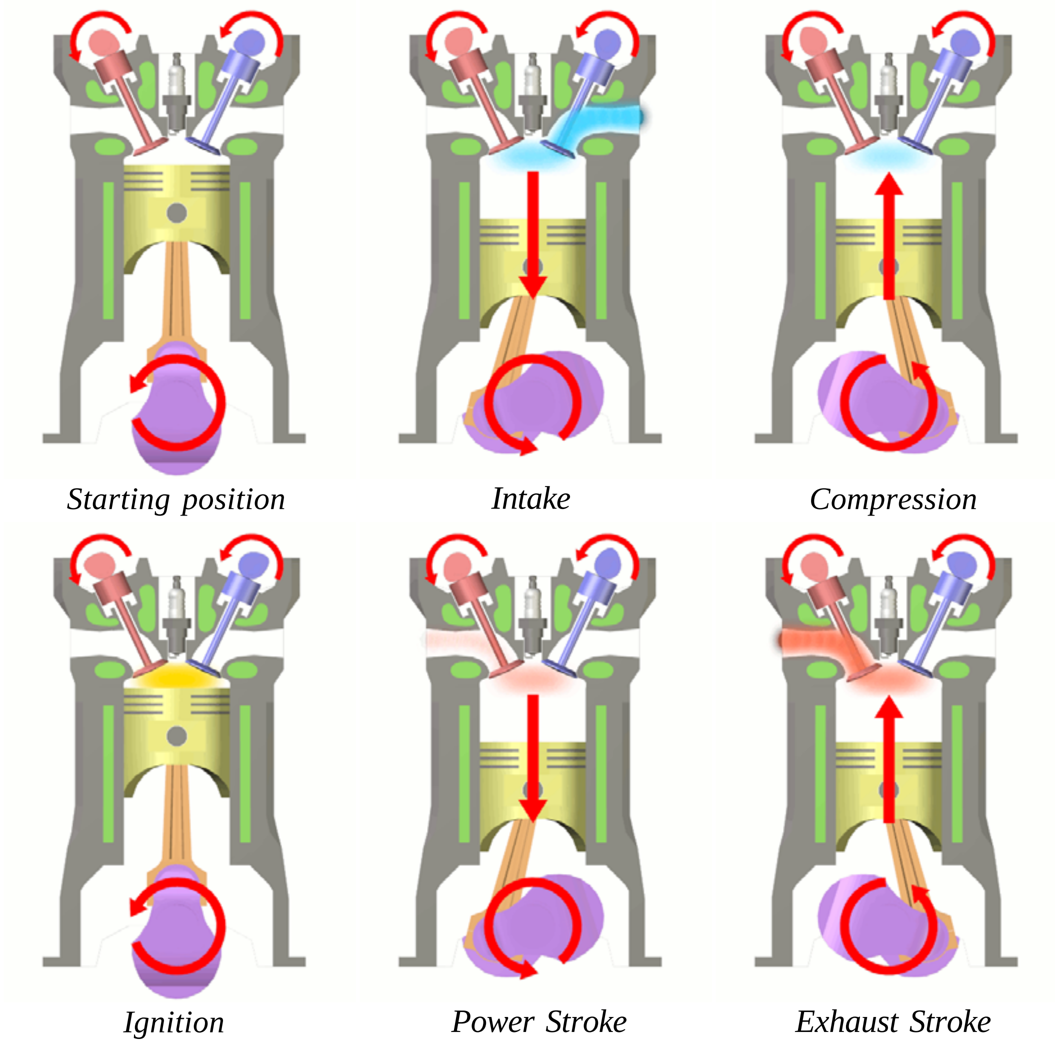


Figure 5.3 Four-stoke Schematic View of SI Engine (Ignition, Power Stroke & Exhaust Stroke)[14]

[14] http://en.wikipedia.org/wiki/Four_stroke

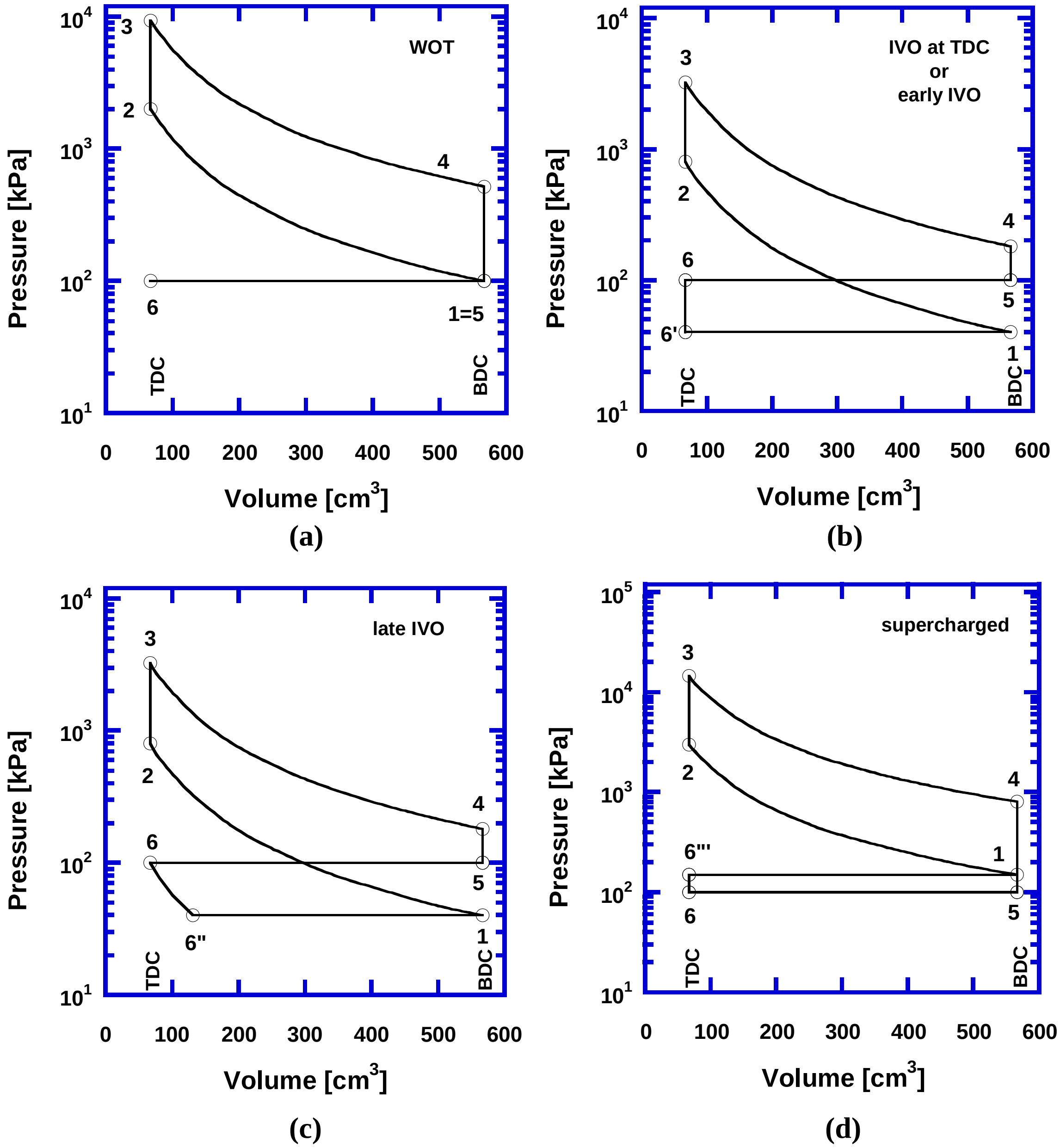


Figure 5.4 Ideal P-V diagrams for the Air Equivalent SI Engine Model; a: WOT, b: early intake, c: late intake, d: supercharged.[15]

[15] R. D. Matthews, Figure 4.8 (2007)

In AESI model sole working fluid is assumed to be air and that explains the "Air" Equivalent SI Engine Model name. Figure 5.4 shows the $P-v$ diagrams of AESI for different engine operating conditions.

Mathematical model will be described in details in the following paragraphs:

The intake process occurs between TDC and BDC and control volume is drawn around the periphery of the combustion chamber for this uniform-state uniform-flow process. First law of the thermodynamics can be applied as:

$Process\ 6-1:$

$$\begin{aligned} &m_6\left(u_6+ke_6+pe_6\right)+ \\ &\sum m_i\left(h_i+ke_i+pe_i\right)-\sum m_e\left(h_e+ke_e+pe_e\right)+Q_{6-1}=m_1\left(u_1+ke_1+pe_1\right)+{}_6W_1 \end{aligned} \tag{5.22}$$

where state 6 is the exhaust residuals and state 1 is the state at the end of the intake process therefore state 1 is the combination of trapped mass inside the cylinder and the fresh air. In addition i refers the inlet and representing the charge entering the cylinder and similarly e refers the exit and representing mass that exits from the cylinder however in the intake process there is not any exiting mass therefore that term equals to zero. Neglecting the kinetic and potential energy terms when compared to the thermal energy terms their effect is insignificant and also assuming intake process is adiabatic one can simplify Equation (5.22) as:

$$m_6u_6+m_ih_i=m_1u_1+{}_6W_1 \tag{5.23}$$

Intake streams from multiple intake valves are combined into an equivalent single intake stream. Work against a moving boundary can be calculated from:

$${}_1W_2=\int_1^2 PdV \tag{5.24}$$

Substituting Equation (5.24) back into Equation (5.23) yields:

$$m_6u_6+m_ih_i=m_1u_1+\int_6^1 PdV \tag{5.25}$$

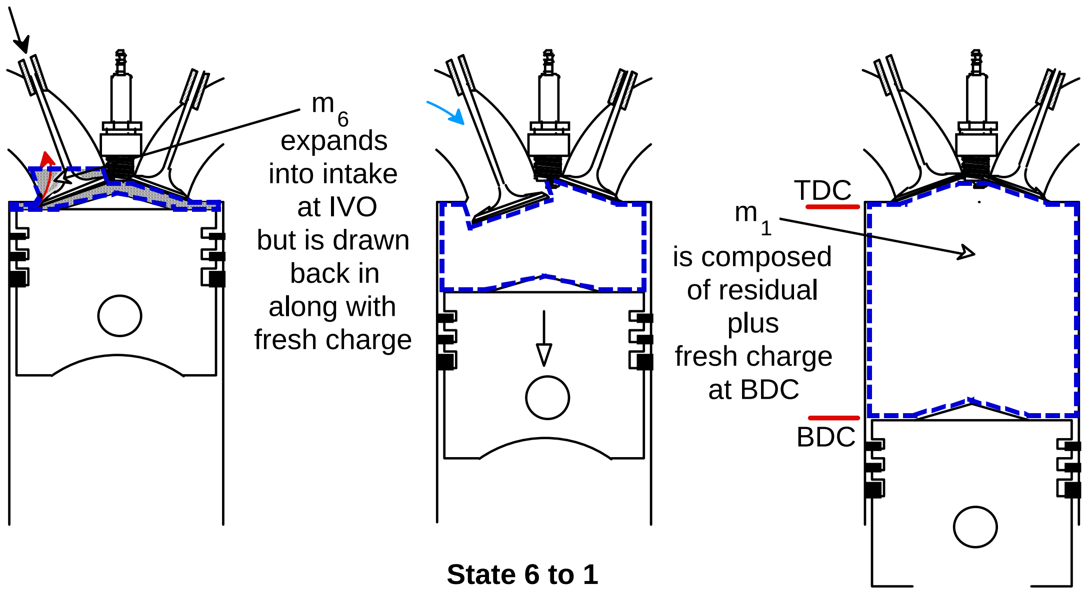


Figure 5.5 Control volume for analysis of intake process.[16]

Conservation of mass principle can be applied over the control volume as shown in Figure 5.5:

$$m_6 + m_i = m_1 \tag{5.26}$$

Exhaust gas residual fraction f can also be defined as:

$$f = \frac{m_6}{m_1} = \frac{m_6}{m_6 + m_i} \tag{5.27}$$

A ratio between mass inducted and the total mass at the end of the intake process can be described in terms of the exhaust gas residual fraction.

$$\begin{aligned} fm_1 + m_i &= m_1 \\ m_i &= (1 - f)m_1 \\ \frac{m_i}{m_1} &= 1 - f \end{aligned} \tag{5.28}$$

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[16] R. D. Matthews, Figure 4.9b (2007)

Work term in Equation (5.25) is changing due to different operating conditions as it is shown in Figure 5.4. The simplest case for the solution of the work done during the intake stroke is the Wide Open Throttle (WOT) operation as can be seen from Figure 5.4 (a). The pressure from state 6 to state 1 is constant therefore integral term can be written as:

$$\begin{aligned} {}_6W_1 &= \int_6^1 PdV \\ &= P_1\left(V_1 - V_6\right) \\ &= m_1P_1v_1 - m_6P_6v_6 \end{aligned} \tag{5.29}$$

It should be noted that it is assumed there is not any pressure drop across valves and it is also assumed that throttle butterfly is fully opened in WOT operation and there is not any pressure drop associated with the throttle body. v_1 is the specific volume of the mixture at the end of the intake stroke and v_6 is the specific volume of the mixture at the end of the exhaust stroke.

For WOT operation one can insert Equation (5.29) back into Equation (5.25):

$$\begin{aligned} m_6u_6 + m_ih_i &= m_1u_1 + m_1P_1v_1 - m_6P_6v_6 \\ m_ih_i &= m_1\left(\underbrace{u_1 + P_1v_1}_{h_1}\right) - m_6\left(\underbrace{u_6 + P_6v_6}_{h_6}\right) \end{aligned} \tag{5.30}$$

$$m_ih_i = m_1h_1 - m_6h_6 \tag{5.31}$$

Mass terms in Equation (5.31) can be represented in terms of exhaust gas residual fraction f by using Equations (5.27) and (5.28):

$$\begin{aligned} \left(1-f\right)m_1h_i &= m_1h_1 - fm_1h_6 \\ \left(1-f\right)\cancel{m_1}h_i &= \cancel{m_1}\left(h_1 - fh_6\right) \\ \left(1-f\right)h_i &= h_1 - fh_6 \end{aligned} \tag{5.32}$$

Rearranging and solving for the enthalpy of the mixture at the beginning of the compression stroke yields:

$$h_1 = \left(1 - f\right) h_i + f h_6 \tag{5.33}$$

Engine is not working all the time at WOT operating condition instead it works dominantly on part throttle operation. The pressure in the intake manifold is less than the pressure in the exhaust manifold because of the pressure drop across the throttle plate in part throttle operation. As it is shown in Figure 5.5 part of the exhaust gasses expand into the intake manifold but it is then sucked back into the cylinder due to pressure difference as can be seen from Figure 5.4 (b). For early intake valve opening (IVO) operation which is the usual case, a similar analysis for the work term can be:

$$\begin{aligned} {}_6W_1 &= {}_6W_{6'} + {}_{6'}W_1 \\ &= \int_6^{6'} PdV + \int_{6'}^{1} PdV \\ &= 0 + P_1\left(V_1 - V_6\right) \\ &= m_1 P_1 v_1 - m_6 P_1 v_6 \end{aligned} \tag{5.34}$$

For early IVO operation one can insert Equation (5.34) back into Equation (5.25):

$$\begin{aligned} m_6 u_6 + m_i h_i &= m_1 u_1 + m_1 P_1 v_1 - m_6 P_1 v_6 \\ m_6\left(u_6 + P_1 v_6\right) + m_i h_i &= m_1 \left(\underbrace{u_1 + P_1 v_1}_{h_1} \right) \\ m_6\left(u_6 + P_1 v_6\right) + m_i h_i &= m_1 h_1 \end{aligned} \tag{5.35}$$

Mass terms in Equation (5.35) can be represented in terms of exhaust gas residual fraction f by using Equations (5.27) and (5.28):

$$f \cancel{m_1} \left(u_6 + P_1 v_6\right) + \left(1 - f\right) \cancel{m_1} h_i = \cancel{m_1} h_1$$
$$f \left(u_6 + P_1 v_6\right) + \left(1 - f\right) h_i = h_1 \tag{5.36}$$
$$h_1 = \left(1 - f\right) h_i + f \left(u_6 + P_1 v_6\right)$$

Although late IVO and supercharged operations are not included in the study, for completeness their enthalpy of the mixture at the beginning of the compression can be expressed as follows for late IVO and supercharged operation respectively:

$$h_1 = \left(1 - f\right) h_i + f h_{6''} \tag{5.37}$$

$$h_1 = \left(1 - f\right) h_i + f h_{6'''} \tag{5.38}$$

Equations (5.33), (5.36), (5.37), and (5.38) are all form of the first law of the thermodynamics and requires the information about the enthalpy of the fresh air charge h_i. This term is expressed in Matthews, 2007 as follows[17]:

$$h_i \approx \frac{1}{1 + FA} h_{a,IV} = \frac{h_{a,TP}}{1 + FA} + \frac{\dot{Q}_{S-a} / \dot{m}_a}{1 + FA} - x_{e,a-f} \frac{FA}{1 + FA} h_{v,f} \tag{5.39}$$

where $h_{a,IV}$ is the specific enthalpy of air entering the combustion chamber, FA is the fuel air ratio, $h_{a,TP}$ is the specific enthalpy of the air crossing the throttle plate, $\dot{Q}_{S-a}$ is the rate of heat transfer from intake surfaces to air, $\dot{m}_a$ is the mass flow rate of air into the engine, $x_{e,a-f}$ is the mass fraction of fuel evaporated due to heat transfer from only the air, and $h_{v,f}$ is the specific enthalpy of vaporization of the fuel at $298K$.

The analysis above allows all of the states of the $P-v$ diagrams to be determined. Therefore one can now define indicated thermal efficiency for the AESI model. Thermodynamically indicated thermal efficiency η_{it} is defined as:

$$\eta_{it} = \frac{w_{net}}{q_{a,th}} \tag{5.40}$$

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[17] R.D. Matthews, Equation 4.66c, 2007

where the net work per unit mass of air is found by summing the work terms around the cycle:

$$w_{net} = {}_1w_2 + {}_2w_3 + {}_3w_4 + {}_4w_5 + w_p \tag{5.41}$$

where w_p is the pumping work per unit mass which is basically the net work required to pump the working fluid into and out of the combustion chamber. Combustion and heat extraction processes considered to be a constant volume processes as can be seen from Figure 5.4, therefore; ${}_2w_3$ and ${}_4w_5$ are both equal to zero.

The total pumping work W_p is the area enclosed between States 5,6, and 1, including the appropriate intermediate states $6'$, $6''$, or $6'''$. For the usual case of early IVO specific pumping work can be mathematically expressed as:

$$\begin{aligned} W_p &= {}_5W_6 + {}_6W_{6'} + {}_{6'}W_1 \\ &= P_6\left(V_2 - V_1\right) + 0 + P_1\left(V_1 - V_2\right) \\ &= \left(P_1 - P_6\right)\left(V_1 - V_2\right) \end{aligned} \tag{5.42}$$

By dividing the Equation (5.42) by the compressed mass m_1, one can get:

$$w_p = \frac{W_p}{m_1} = \left(P_1 - P_6\right)\left(v_1 - v_2\right) \tag{5.43}$$

Remaining work terms in Equation (5.41) ${}_1w_2$ and ${}_3w_4$ can be determined from the first law of the thermodynamics, thus following expression can be obtained for the early IVO by inserting Equation (5.43) into Equation (5.41):

$$w_{net} = \left(u_1 - u_2\right) + \left(u_3 - u_4\right) + \left(P_1 - P_6\right)\left(v_1 - v_2\right) \tag{5.44}$$

For WOT operation $\left(P_1 - P_6\right)\left(v_1 - v_2\right)$ term in Equation (5.44) drops since there is not any pumping work is necessary in WOT operation.

Thermal energy per unit mass of trapped mixture can be obtained by the following equation. A detailed analysis is available at Matthews, 2007[18].

$$q_{a,th} = \eta_c \left[\left(1 - f\right) LHV_P \frac{FA}{1 + FA} \right] \tag{5.45}$$

5.5.2 AESI Indicated Thermal Efficiency Solution Procedure

In this section an iterative algorithm will be presented to find an indicated thermal efficiency for an operating condition of the SI engine.

1) Combustion efficiency can be determined by Section 5.3.
2) Two intensive properties needed to fix State 1 however, only pressure is known. Therefore, make a guess for residual fraction f and the temperature of the mixture trapped at the beginning of the compression stroke T_1.
3) Pressure of the State 1 is assumed to be equal to atmospheric pressure for WOT operation since it is assumed that there are no flow losses at throttle and inlet manifold. And for early IVO pressure can be modeled by means of the $LOAD$ since the throttle plate opening angle can be related with $LOAD$, when throttle plate is fully closed it is assumed that the $P_1 = 33kPa$.

$$\begin{aligned} P_1 &= P_{ex} && \text{(WOT)} \\ P_1 &= \left(P_{ex} - 33\right) LOAD + 33 && \text{(early IVO)} \end{aligned} \tag{5.46}$$

4) Specific volume of the State 1 can be found via ideal gas law for air:

$$v_1 = \frac{R_a T_1}{P_1} \tag{5.47}$$

5) Since the compression process from State 1 to State 2 is isentropic and the only working fluid is air thus relative specific volume v_r relationship can be used.

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[18] R. D. Matthews, Equation 4.83d, 2007

$$\frac{v_{r,1}}{v_{r,2}} = \frac{v_1}{v_2} = r_c \tag{5.48}$$

where, r_c is the compression ratio. $v_{r,1}$ can be found by using the air thermodynamics table by assuming air as an ideal gas. A MATLAB code is supplied in Appendix C.4 which is used to calculate air properties in the model.

$$v_{r,2} = \frac{v_{r,1}}{r_c} \tag{5.49}$$

By using Equation (5.49) one can calculate the relative specific volume of the State 2, $v_{r,2}$, and thus the other state properties T_2 and u_2 can be read from the thermodynamics table of ideal gas air.

6) It is known that from Figure 5.4 the volume is constant during combustion process of 2-3. Thus,

$$v_3 = v_2 \tag{5.50}$$

where:

$$v_2 = \frac{v_1}{r_c} \tag{5.51}$$

1st Law of Thermodynamics:

$$u_2 + q_{a,th} = u_3 + {}_2w_3 \tag{5.52}$$

Work term is zero since the volume does not change. And heat addition term is expressed by Equation (5.45). Therefore u_3 can be calculated by Equation (5.52) and this enables to find properties of the State 3, T_3, $v_{r,3}$, and $s^0_{T_3}$, through the thermodynamics table of ideal gas air.

$$P_3 = P_{max} = \frac{R_a T_3}{v_3} \tag{5.53}$$

7) Process 3-4 is isentropic expansion and relative specific volume of the State 4 can be found by:

$$v_{r,4} = v_{r,3} \times r_c \tag{5.54}$$

Therefore, temperature at the end of the expansion process, $T_4 = T_{EVO}$, can be read from air tables.

8) It will be assumed that working fluid that remains inside the combustion chamber after the combustion process, State 4, expands isentropically to the exhaust manifold pressure during the exhaust blowdown, which is assumed to occur at constant volume at BDC as it is shown in Figure 5.6.

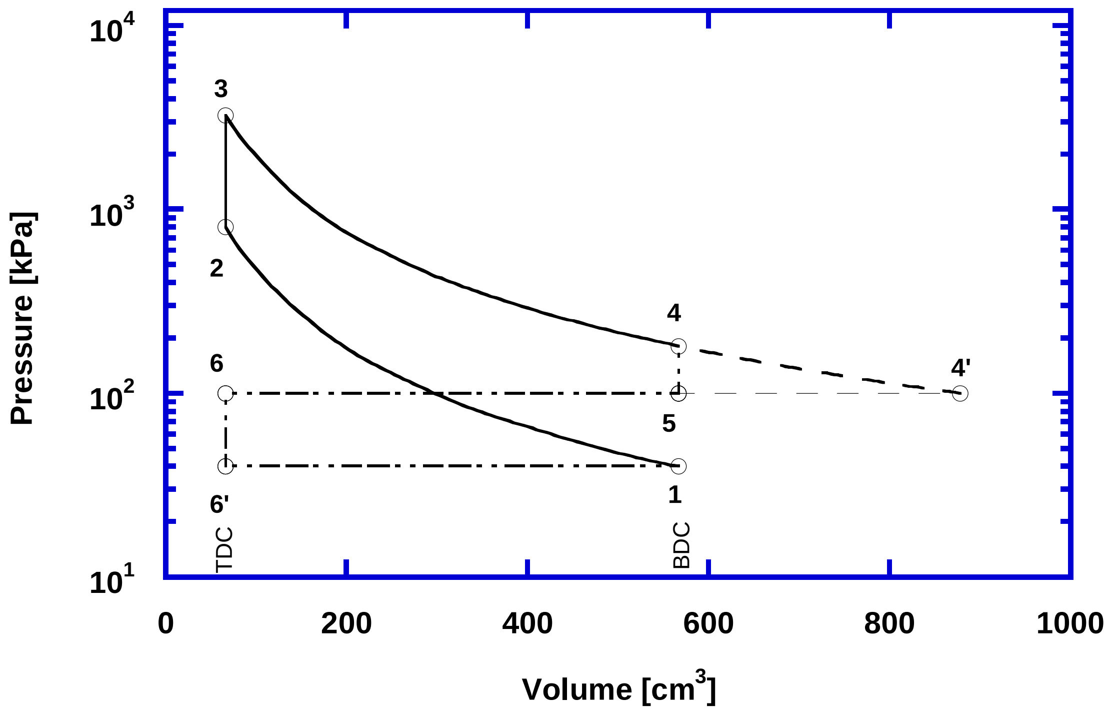

Figure 5.6 Ideal $P-V$ diagram for analysis of the exhaust process, including State $4'$.[19]

Dashed lines from 4 to $4'$ to 5 indicate "imaginary" parts of the cycle. Dot-dash lines indicate open portions of the cycle (mass loss or gain). State $4'$ represents

[19] R. D. Matthews, Figure 4.10, 2007

the state of the working fluid that remains within the combustion chamber during the exhaust blowdown process. As it can be seen from the Figure 5.6, pressure at State $4'$ equals to pressure at State 5 and pressure at State 6 which is the exhaust manifold pressure and assumed to be equal to atmospheric pressure.

$$P_{4'} = P_5 = P_6 = P_{ext} \tag{5.55}$$

Since the process $3-4'$ is isentropic one can write following equation for change of specific entropies of the ideal gases:

$$s_{4'} - s_3 = 0 = s^0_{T_{4'}} - s^0_{T_3} - R_a \ln\left(\frac{P_{4'}}{P_3}\right) \tag{5.56}$$

Rearrange to get:

$$s^0_{T_{4'}} = s^0_{T_3} + R_a \ln\left(\frac{P_{4'}}{P_3}\right) \tag{5.57}$$

$T_{4'}$ can be found by using the thermodynamic tables since $s^0_{T_{4'}}$ is known. It is also known that there is not any heat transfer occurs between States $4'$, 5, and 6. And also during the exhaust stroke, the working fluid in State $4'$ undergoes an isentropic process. If one writes Equation (5.56) between these states the pressure term will be zero since all pressure terms are zero as stated in Equation (5.55). Thus, standard state entropies for these states will be equal to each other, which imply all thermodynamic properties of these states will be identical.

$$\begin{aligned} T_{4'} &= T_5 = T_6 \\ h_{4'} &= h_5 = h_6 \end{aligned} \tag{5.58}$$

Specific volume of the State $4'$ can be calculated by:

$$v_{4'} = \frac{R_a T_{4'}}{P_{4'}} \tag{5.59}$$

Since temperatures and pressures in States $4'$, 5, and 6 are same their specific volumes should also be same:

$$v_{4'} = v_5 = v_6 \tag{5.60}$$

9) Initial guesses of exhaust gas residual fraction f and temperature before compression T_1 needs to be checked to continue analysis.

It is known from Equation (5.27) that:

$$f = \frac{m_6}{m_1} \tag{5.61}$$

Exhaust gas residual fraction can be calculated with known properties of the States 2 and $4'$:

$$f_{new} = \frac{m_6}{m_1} = \frac{V_6 / v_6}{m_1} = \frac{V_2 / v_{4'}}{m_1} = \frac{V_2 / m_1}{v_{4'}} = \frac{V_2 / m_2}{v_{4'}} = \frac{v_2}{v_{4'}} \tag{5.62}$$

New residual fraction should be in the 0.5% of the assumed residual fraction:

$$0.995 f \le f_{new} \le 1.005 f \tag{5.63}$$

Equations (5.33) and (5.36) can be used to calculate specific enthalpy of the trapped mixture at the beginning of the compression process h_1 for WOT and early IVO operations respectively.

$$\begin{aligned} h_1 &= (1-f)h_i + fh_6 && \text{(NA @ WOT)} \\ h_1 &= (1-f)h_i + f\left(u_6 + P_1 v_6\right) && \text{(early IVO)} \end{aligned} \tag{5.64}$$

Enthalpy of fresh charge h_i can be calculated from Equation (5.39).

$$h_i \approx \frac{1}{1+FA} h_{a,IV} = \frac{\overbrace{h_{a,TP}}^{@298K}}{1+FA} + \underbrace{\frac{\dot{Q}_{S-a} / \dot{m}_a}{1+FA}}_{0} - \underbrace{x_{e,a-f}}_{0.15} \frac{FA}{1+FA} \underbrace{h_{v,f}}_{303.6 kJ/kg} \tag{5.65}$$

Specific enthalpy of the air is calculated at $298K$ and it is assumed there is not a heat transfer from intake surfaces to air. Moreover evaporation rate for the gasoline is typically 15% and for a generic gasoline heat of vaporization $h_{v,f}$ is $303.6\, kJ/kg$.

The temperature T_1 corresponding to calculated enthalpy h_1 can be determined using air tables. Error in new T_1 should be less than 5%:

$$0.995T_1 \le \left(T_1\right)_{new} \le 1.005T_1 \tag{5.66}$$

If new f and T_1 does not satisfy the requirements of 5% error then recalculate these parameters by using the new values of f and T_1 until (5.63) and (5.66) are satisfied.

10) Since all states are fixed now indicated thermal efficiency can be calculated by Equation (5.40).

$$\eta_{it} = \frac{w_{net}}{q_{a,th}} \tag{5.67}$$

where heat terms is expressed by Equation (5.45):

$$q_{a,th} = \eta_c \left[\left(1 - f\right) LHV_P \frac{FA}{1 + FA} \right] \tag{5.68}$$

and work term is expressed by Equation (5.44) for early IVO operation:

$$w_{net} = \left(u_1 - u_2\right) + \left(u_3 - u_4\right) + \left(P_1 - P_6\right)\left(v_1 - v_2\right) \tag{5.69}$$

for WOT operation pumping work term becomes zero, thus; work term for WOT operation can be written as:

$$w_{net} = \left(u_1 - u_2\right) + \left(u_3 - u_4\right) \tag{5.70}$$

Indicated thermal efficiency calculated with this model is multiplied by a factor of 0.5 to approach real operating values of the indicated thermal efficiency. A heat addition model will be added to this model for better estimation in next step of this study.[20]

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[20] G. Woschni

5.5.3 Fuel Economy Model Graphical User Interface

The physical model explained in this chapter is coded with MATLAB for broader engine operating conditions and faster computation purposes. Thus, MATLAB codes are wrapped with a C# Graphical User Interface (GUI) on the .NET platform of Windows to deliver the computational capability to users who does not have MATLAB installed on their computers with full power of the MATLAB.

Following figure shows the welcome screen of the Fuel Economy Model GUI. Program expects user to enter some engine design parameters, tires specifications in addition to drivetrain gear ratios.

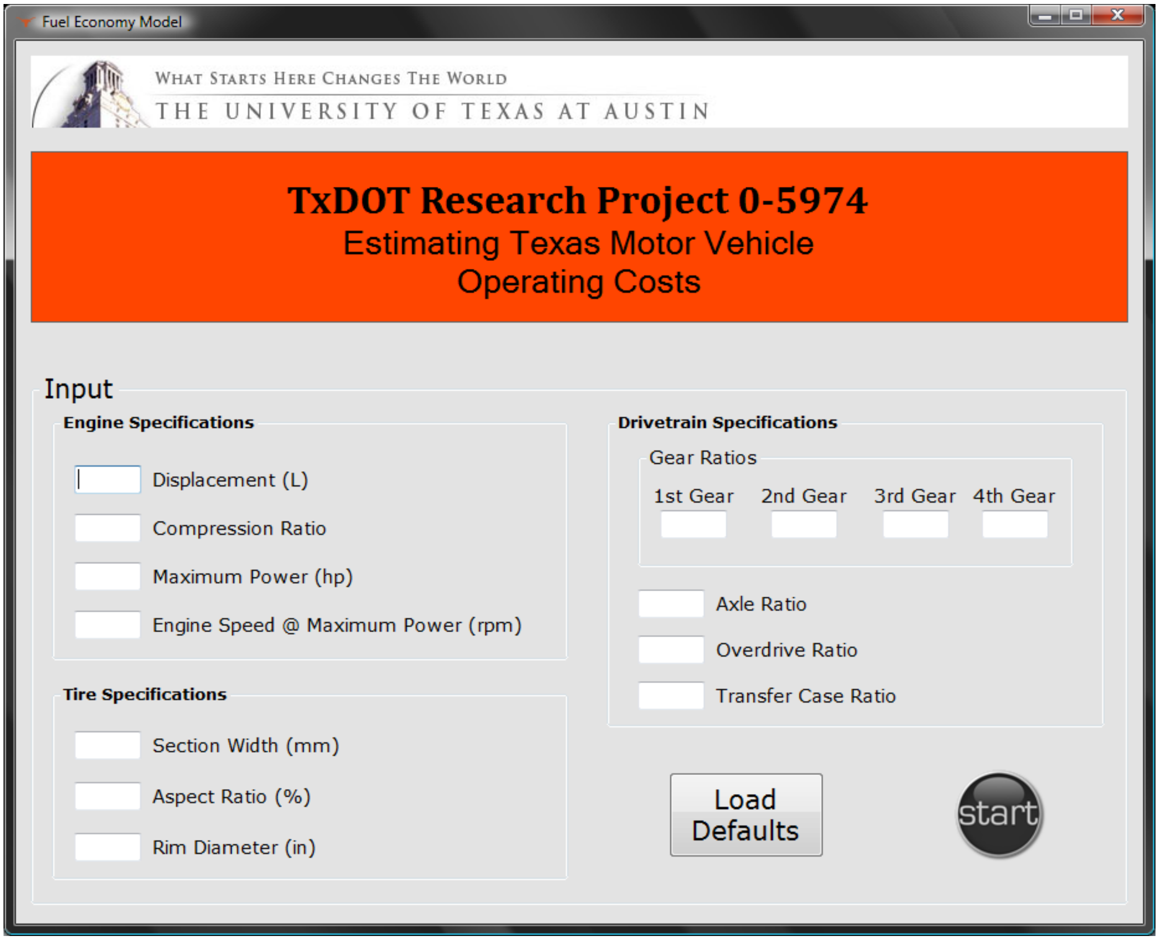


Figure 5.7 Welcome screen of the Fuel Economy Model

Figure 5.8 shows the default values entered by pressing the "Load Defaults" button for the Ford F-150 full size 4WD pickup.

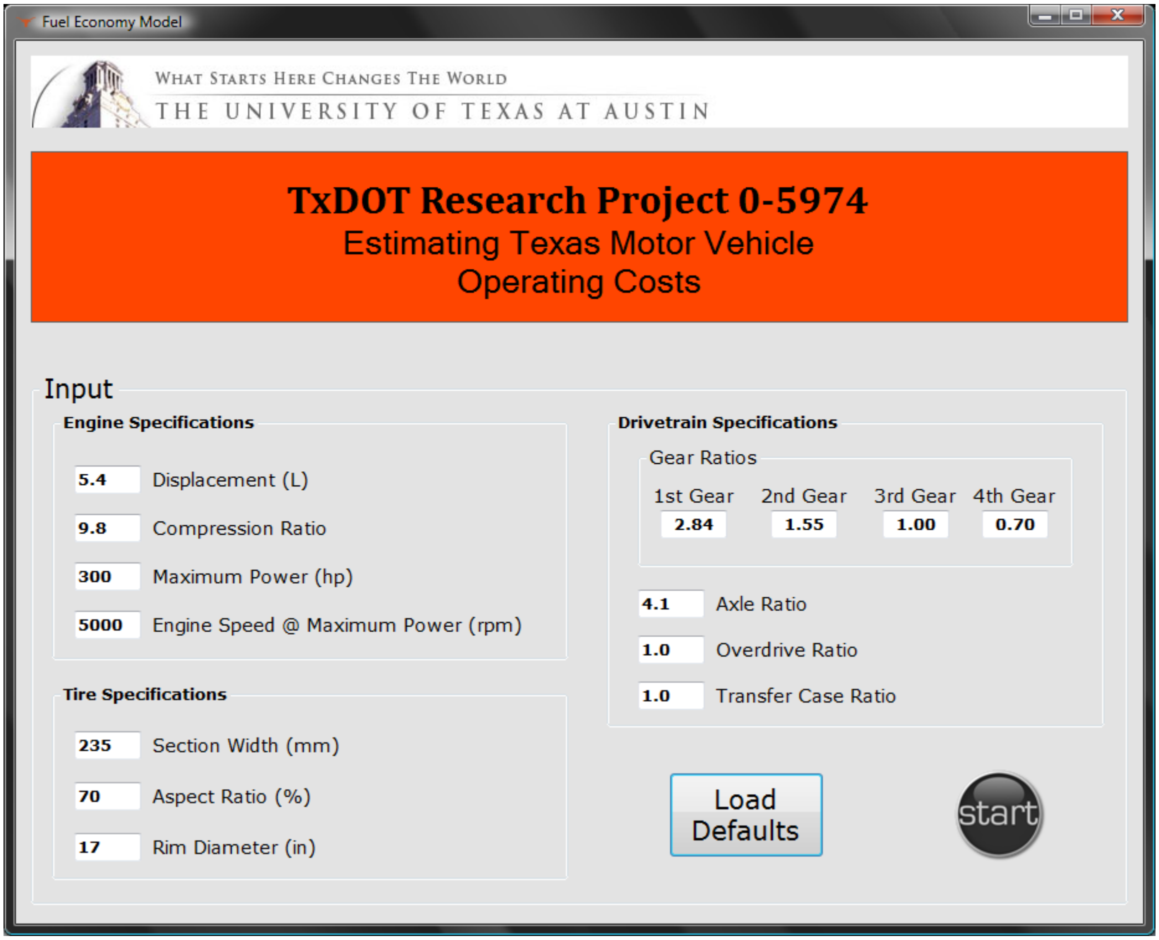


Figure 5.8 Default values of Ford F150 are loaded to Fuel Economy Model

Figure 5.9 shows the Fuel Economy versus Speed graph for the default values of the Fuel Economy Model. It is a MATLAB figure screen and having full power of the MATLAB inside which makes this software very different. First Excel spreadsheet model of the Fuel Economy Model is shown in Figure 5.10 also. MATLAB and C# codes can be found in Appendix C: Codes of Vehicle Specific Fuel Economy Model.

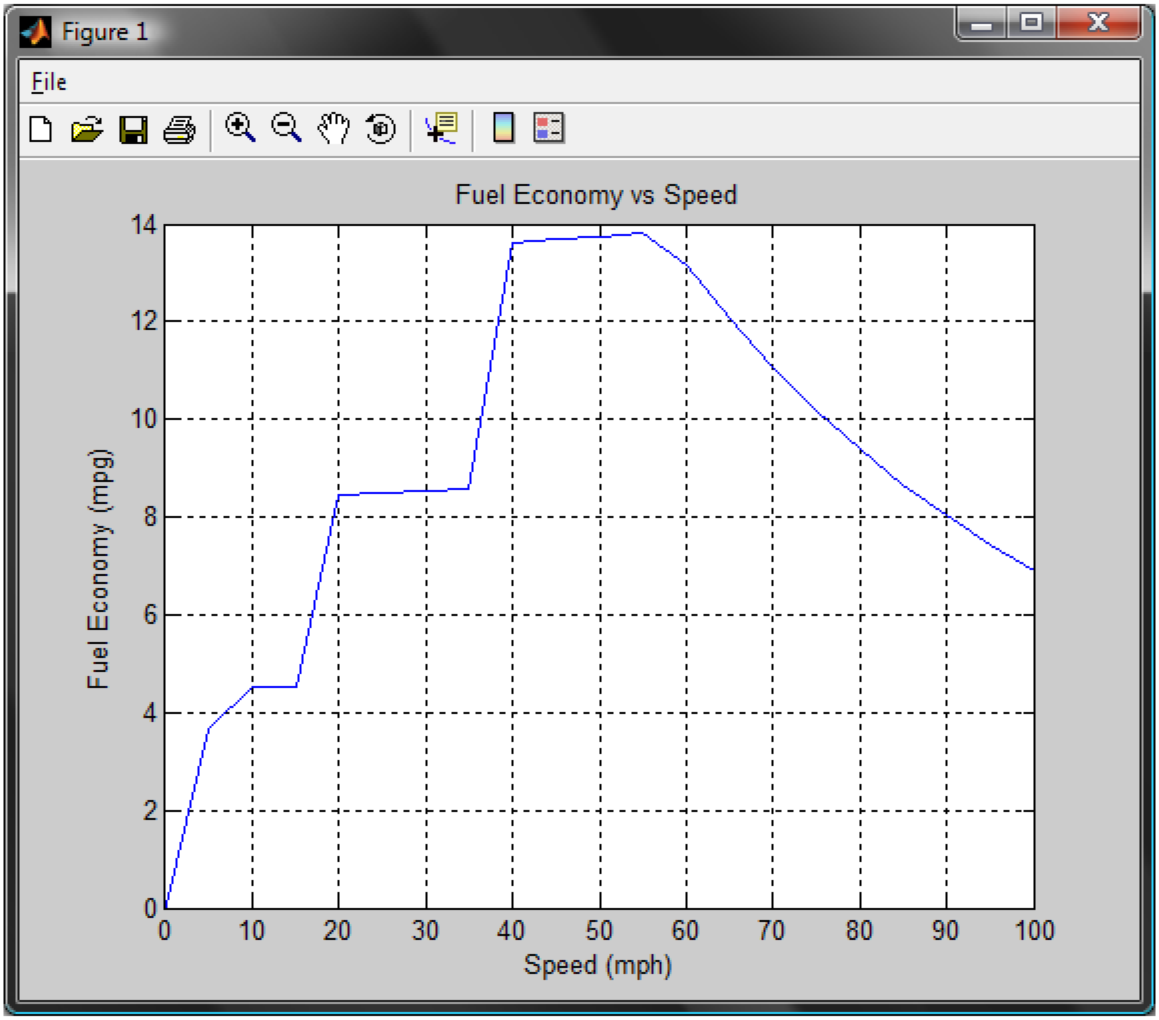


Figure 5.9 Result screen of the Fuel Economy Model

Microsoft Excel - gal per 100 miles calculation.xlsx

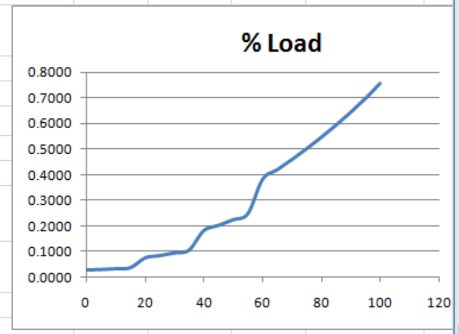
FORD F150 PICKUP 4WD

η_{city}	η_{hway}	ρ_{air} (kg/m^3)	ρ_{fuel} (kg/m^3)	LHV (MJ/kg)	A	B	C	CV2	FTP avg velocity (mph)	HWFET avg velocity (mph)	m (slope)	constant
0.257665	0.28521581	1.203	744.255	44.6	47.7	1.0532	0.03339	0.000525315	21.2	48.2	0.001	0.236

D_{tire} (in)	Disp. (L)	η_c	η_{ti}	η_{ti}*η_v	η_T	η_D	ϕ	FA_s	x	r_c	Stroke (in)
29.953	5.4	0.96	0.30	0.329	0.90	0.95	1.000	0.06897	2	9.8	4.17

Tire Specification			Gear Ratios				Axle Ratio	Overdrive Ratio	Transfer Case Ratio	Max Power		Idle Power
Section Width	Aspect Ratio	Wheel Diameter	1	2	3	4	4.1	1.00	1.00	rpm	5000	850
235	70	17	2.84	1.55	1.00	0.70				bp (hp)	300	51

bp equation			Drag		Rolling resistance		Vehicle Weight	
m (slope)	constant	τ_{bp} (Nm)	C_D	$A_{frontal}$ (m^2)	C_R^o	C_R'	W_v (lbf)	$W_{payload}$ (lbf)
0.060	0.000	427.25	0.422	2.133	0.0125	5E-05	7000	



Velocity (mph)	Gear	Gear Ratio	η_T	η_D	η_{ti}	N (rpm)	fp (hp)	bp (hp)	$bp_{required}$ (hp)	% Load	$\eta_{m\,(normalized)}$	η_m	F_{RL} (lbf)	FE (mpg)	gal/100 miles	Effs	$F_{RL\,(fundamental)}$ (lbf)
0.1	1	2.84	0.85	0.67	0.02	13	0.00	0.78	0.02	0.0287	0.10	1.00	47.8	0.460	217.41	0.001253	87.50
5	1	2.84	0.85	0.69	0.08	653	2.02	39.20	1.22	0.0310	0.11	0.95	53.8	1.624	61.56	0.004979	88.22
10	1	2.84	0.85	0.72	0.14	1307	8.10	78.40	2.67	0.0341	0.12	0.91	61.6	2.648	37.76	0.009289	90.37
15	1	2.84	0.85	0.75	0.18	1960	18.22	117.60	4.46	0.0379	0.13	0.87	71.0	3.505	28.53	0.014181	93.96
20	2	1.55	0.87	0.77	0.14	1426	9.65	85.58	6.50	0.0760	0.26	0.90	82.1	5.162	19.37	0.024152	98.98
25	2	1.55	0.87	0.80	0.17	1783	15.07	106.98	9.11	0.0852	0.29	0.88	94.9	6.027	16.59	0.032585	105.44
30	2	1.55	0.87	0.82	0.19	2140	21.71	128.37	12.25	0.0954	0.32	0.86	109.3	6.801	14.70	0.042366	113.33
35	2	1.55	0.87	0.84	0.21	2496	29.55	149.77	15.99	0.1068	0.36	0.84	125.5	7.484	13.36	0.053493	122.66
40	3	1	0.88	0.86	0.17	1840	16.06	110.43	20.16	0.1825	0.62	0.87	143.3	9.545	10.48	0.077898	133.42
45	3	1	0.88	0.88	0.19	2070	20.33	124.23	25.22	0.2030	0.69	0.86	162.7	10.320	9.69	0.095664	145.62
50	3	1	0.88	0.90	0.20	2301	25.10	138.03	31.06	0.2250	0.77	0.85	183.8	11.036	9.06	0.115591	159.25
55	3	1	0.88	0.91	0.21	2531	30.37	151.84	37.74	0.2486	0.85	0.83	206.6	11.695	8.55	0.137671	174.31
60	4	0.7	0.9	0.93	0.18	1932	17.71	115.95	44.34	0.3824	0.85	0.87	231.1	9.211	10.86	0.12127	190.82

Chart1 Chart3 Sheet1 Sheet2 Chart2 Sheet3

Figure 5.10 Excel Spreadsheet of the Fuel Economy Model

A setup file also created for easy distribution of the software. Following figure shows the welcome screen of the Fuel Economy Model GUI.

Figure 5.11 Welcome screen of the Fuel Economy Model installation.

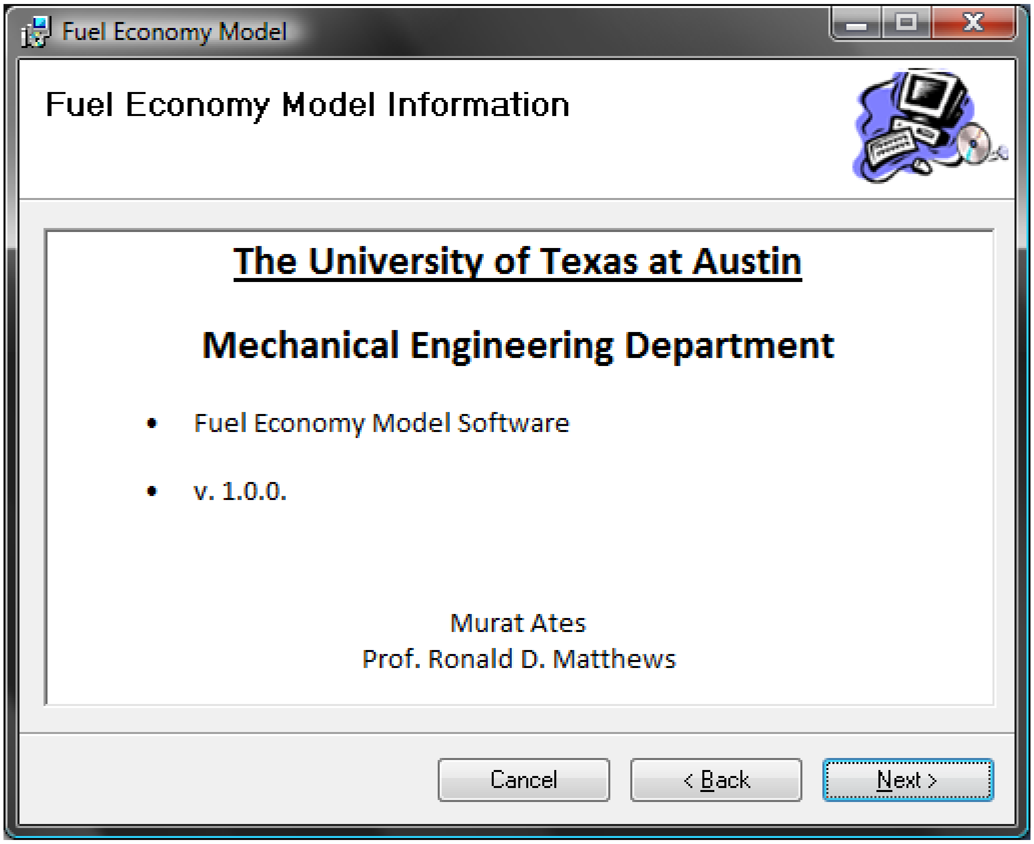


Figure 5.12 Information screen about the software and the developers

Figure 5.12 shows the information screen of the Fuel Economy Model, version number of the model and institution info who holds the copyright is given in addition to names of the engineers who developed the software.

GNU General Public License is used for free distribution of the software as shown in Figure 5.13.

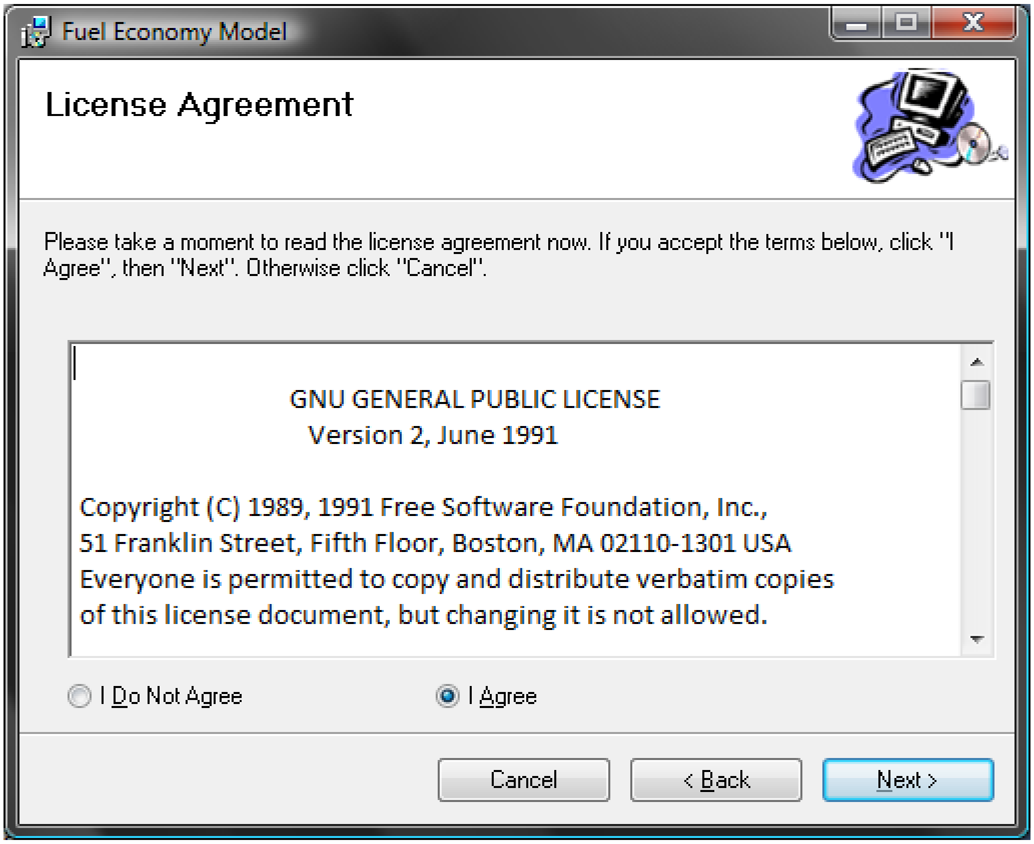


Figure 5.13 GNU License Agreement screen of the Fuel Economy Model

Chapter 6 SAE Coastdown Practice[21]

6.1 OVERVIEW

This procedure is adopted from SAE Recommended Practice J1263. Definitions, procedures regarding coastdown tests will be explained in this chapter.

6.2 TECHNICAL BACKGROUND

Physical equations governing coastdown tests are explained in Chapter 2 and detailed analysis is given in Chapter 7.

6.3 ROAD LOAD MEASUREMENT USING COASTDOWN TECHNIQUES

6.3.1 Scope

This procedure covers measurement of vehicle road load on a straight, level road at speeds less than 70 mph.

6.3.2 Purpose

The purpose is to provide a uniform testing procedure for measuring the road load force and determining coastdown coefficients A, B, and C on a vehicle through vehicle speed versus time data.

6.4 DEFINITIONS

6.4.1 Test Weight

Test weight is the weight of the vehicle as tested; including driver, operator (if necessary), and all instrumentation.

[21] SAE J1263

6.4.2 Test Mass

Test mass is the mass of the vehicle as tested; including driver, operator (if necessary), and all instrumentation.

6.4.3 Effective Mass

Effective mass is equal to the sum of the test mass and the effective inertias of the driven and non-driven axles.

6.4.4 Frontal Area

Frontal area is the area of the orthogonal projection of the vehicle including tires and suspension components onto a plane perpendicular to the longitudinal axis of the vehicle.

6.5 VEHICLE ROAD LOAD MEASUREMENT

6.5.1 Instrumentation

All instrumentation must be calibrated for each vehicle.

6.5.2 Time and Speed

An instrument to measure vehicle speed as a function of elapsed time is used in this procedure. The device must meet the following specifications:

a) Time:
   i. Accuracy $\pm 0.1\%$ of total coastdown time interval
   ii. Resolution 0.1 s

b) Speed:
   i. Accuracy ± 0.25 *mph*
   ii. Resolution 0.1 *mph*

6.5.3 Temperature

The temperature indicating devices must have a resolution of $2\ ^0F$ and an accuracy of $\pm 2\ ^0F$. The sensing element must be shielded from radiant heat sources.

6.5.4 Atmospheric Pressure

A barometer with an accuracy of $\pm 0.7\ kPa$ or $\pm 0.2\ in-Hg$ is necessary.

6.5.5 Wind

Wind speed and direction during the test should be continuously monitored. Wind measurements should permit the determination of average longitudinal and crosswind components within $\pm 1\ mph$.

6.5.6 Vehicle Weight

Vehicle weight should be measured to an accuracy of $\pm 10\ lb$ per axle.

6.5.7 Tire Pressure

Tire pressure should be measured to an accuracy of $\pm 0.5\ psi$.

6.6 TEST CONDITIONS

6.6.1 Ambient Temperature

Tests may be conducted at ambient temperatures between $30\ ^0F$ and $90\ ^0F$. The recommended temperature range is from $41\ ^0F$ to $90\ ^0F$. Data obtained at temperatures outside this range cannot be reliably adjusted to standard conditions by Section 7.4.

6.6.2 Winds

Tests may not be conducted when wind speeds average more than $10\ mph$ (or when peak wind speeds are more than $12.3\ mph$). The average of the component of the wind velocity perpendicular to the test road may not exceed $5\ mph$.

6.6.3 Road Conditions

Roads must be dry, clean, smooth, and must not exceed 0.5% grade. In addition, the grade should be constant and the road should be straight since variations in grade or straightness can significantly affect results. The road surface should be concrete or rolled asphalt (or equivalent) in good condition since rough roads can significantly affect rolling resistance. In addition, tests may not be run during foggy or rainy conditions: roads must be dry.

6.7 VEHICLE PREPARATION

6.7.1 Break-In

The test vehicle should have accumulated a minimum of 300 miles prior to testing. The tires should have accumulated a minimum of 100 miles and should have at least 75% of the original tread depth remaining.

6.7.2 Vehicle Check-In

The following items should be compared to manufacturer's recommendation and recorded on the Appendix D: Vehicle Road Test D prior to test:

a) Tire type, size, and cold inflation pressure (see Section 6.7.4)
b) Wheel size, conditions, and presence of wheel covers
c) Brake adjustment
d) Lubricants in the drivetrain and in the non-driving wheel bearings
e) Vehicle suspension heights

6.7.3 Instrumentation

The speed-time measuring device and other necessary equipment must be installed so that they do not hinder vehicle operation or alter the operating characteristics of the vehicle.

6.7.4 Tire Pressure

Inflate the tires of the test vehicle to the manufacturer's recommended cold inflation pressure, corrected for the temperature difference (if any) between the vehicle tires and the test area. The tire pressure should be increased $1\,psi$ for each $13\ ^0F$ that the vehicle preparation area temperature the test is above the test temperature. Record the actual inflation pressure and preparation area temperature on the Appendix D: Vehicle Road Test D.

6.7.5 Vehicle Frontal Area

The vehicle frontal area must be known, measured, or estimated and the value recorded on the Appendix D: Vehicle Road Test D. The frontal area will be estimated by taking a front picture of the vehicle with a reference area in that picture. Frontal area than will be calculated through pixel comparison with known area.

6.7.6 Vehicle Warm-Up

The vehicle must be driven a minimum of 30 min at an average speed of $50\ mph$ immediately prior to the test.

6.8 COASTDOWN TEST

6.8.1 Alternating Directions

A minimum of 10 runs are made in alternating directions. The runs must be paired for the data reduction process in order to reduce error.

6.8.2 Procedure

The vehicle windows must be closed. At the start of each run, accelerate the vehicle to $65\ mph$, start the recording equipment, and shift into neutral and let the engine idle. The vehicle clutch must be engaged. When the vehicle stops, stop the recording equipment, engage the transmission, and prepare for the next run.

6.8.3 Lane Changes

While coasting, lane changes should be avoided if at all possible. If necessary, they should be done as slowly as possible and over a distance of at least a quarter mile. If such a gradual change cannot be made, abort the run.

6.8.4 Data to be Recorded

Record the direction and number of each run (including aborted runs) in such a way that the speed time data can be separated by run number. Record the ambient temperature and atmospheric pressure after warm-up and after the test. Average the two values to determine the value to be used in the data reduction.

The total wind and either the wind direction or the crosswind component of the total wind must be recorded. The wind quantities should be recorded, screened for gusts exceeding the ambient conditions limit in Section 6.6.2, and averaged. Record the results on the Appendix D: Vehicle Road Test D.

6.8.5 Vehicle Test Weight

After the coastdown run, weight the vehicle to determine the vehicle test weight or mass. Include the weight of the spare wheel, driver, and all instrumentation used. Record the weight on the Appendix D: Vehicle Road Test D.

Chapter 7 Analytical Basis of Coastdown Testing[22] [23] [24]

7.1 OVERVIEW

The problem of aerodynamic and rolling resistance characteristics of cars and trucks is of considerable importance to vehicle engineers as the two major contributions to external vehicle drag. Many testing methods have been developed including wind tunnel testing of scale models, testing of full-size production cars, and coastdown testing. Wind tunnel testing is well applied in the aircraft industry and when applied to the automotive industry it raised numerous questions on ground affects and rolling affects of the tires. Moreover model scaling problems arise due to Reynolds number, boundary layer transition, and separation. Technical simulation problems and high cost is a drawback for wind tunnel testing.

On the other hand, the coastdown technique simulates the real world cases because of the nature of the test. The simplicity and inexpensiveness of the coastdown tests make the test industry standard. Federal Tests Procedures require the use of chassis dynamometers for fuel economy and emissions testing. These dynamometers must simulate both the dynamic and steady state loads on the vehicle drivetrain for such tests to provide an accurate representation of road experience.

Coastdown testing has been accepted by the United States Environmental Protection Agency as means of determining a power absorbing setting which simulates the road load of the vehicle. Currently, a coastdown of the car-dynamometer system is

[22] R. A. White and H. H. Korst
[23] T. P. Yasin
[24] SAE J1263

used to match the load on the drive line at fifty miles per hour to that determined from the road tests.

7.2 ANALYSIS

Typical coastdown test data can be presented in the form of velocity versus time curves similar to Figure 7.1.

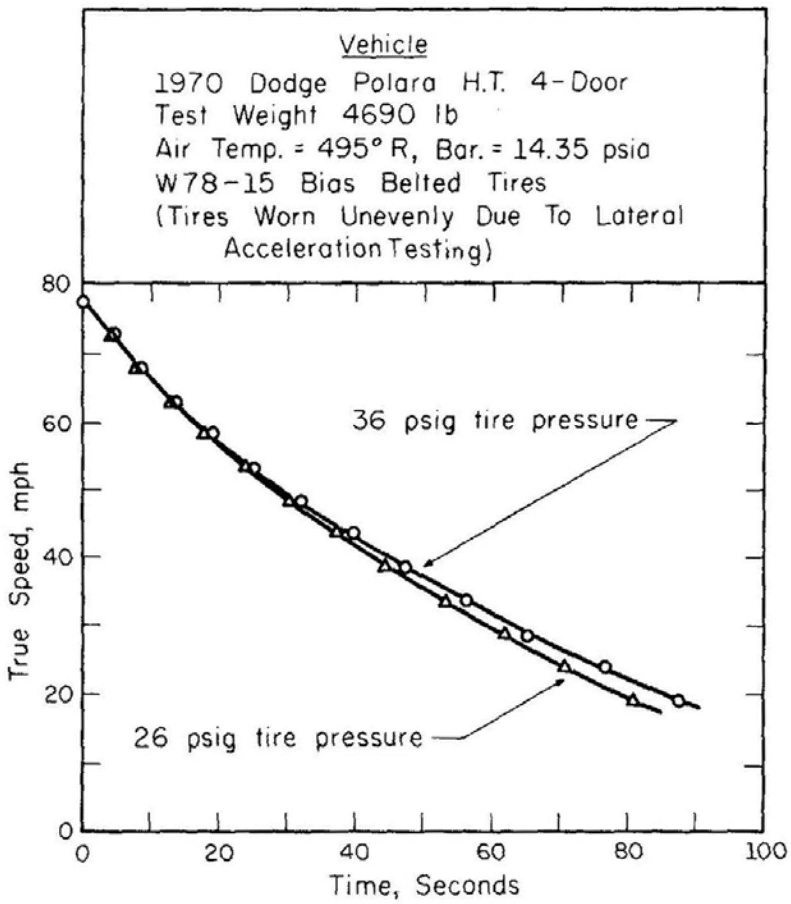


Figure 7.1 Velocity vs. Time of Typical Coastdown Test[25]

[25] R. A. White and H. H. Korst

The following analysis is intended to define the form of the major forces acting on a vehicle as a function of speed. It is assumed that:

- Road grade is zero
- Wind speed is less than vehicle speed
- Wind speed is steady
- There is not any major gust
- Aerodynamic yaw angles remain small

In Chapter 2 forces resisting the vehicle's movement described and formulated with Equation (2.1). Road grade is assumed to be zero, therefore $F_G = 0$ and Equation (2.1) can be written as sum of aerodynamic and tire and chassis drag forces:

$$F_{RL} = F_D + F_R \tag{7.1}$$

Resistive force is identified as road load force due to absence of wind and grade as it is explained in Section 2.4.

Ambient conditions affect these force components differently, so that each must be analyzed separately.

7.2.1 Aerodynamic Forces

Three mutually perpendicular forces: drag, lift, and side act on the vehicle. The forces take the form:

$$X = C_X A q \tag{7.2}$$

where:

X : is any one of the three aerodynamic forces
C_X : is the coefficient of the force X
A: is the reference (frontal) area
q: is the dynamic pressure of the airstream

By definition,

$$q = \frac{\rho v_a^2}{2} \tag{7.3}$$

where:

ρ: is air density and

v_a: is the total relative airspeed

Ideal gas law can be written as:

$$P = \rho R T \tag{7.4}$$

where:

R: is gas constant and

T: is absolute temperature

Air density varies with absolute temperature and barometric pressure by:

$$\frac{\rho}{\rho_0} = \left(\frac{P}{P_0}\right)\left(\frac{T_0}{T}\right) \tag{7.5}$$

where $\rho_0, P_0,$ and T_0 are respectively density, pressure, and absolute temperature of a reference condition. The total effect of humidity on air density is less than 1% at normal test temperatures and can be neglected.

In the presence of a wind of speed v, having components Sv_x and v_y parallel and perpendicular to the vehicle's path respectively and S is ±1 depending on vehicle coastdown direction; v_a will be related to vehicle ground speed V as shown in Figure 7.2 by:

$$v_a = \sqrt{\left(V + Sv_x\right)^2 + v_y^2} \tag{7.6}$$

Thus, Equation (7.3) becomes:

$$q = \frac{\rho\left[\left(V + Sv_x\right)^2 + v_y^2\right]}{2} \tag{7.7}$$

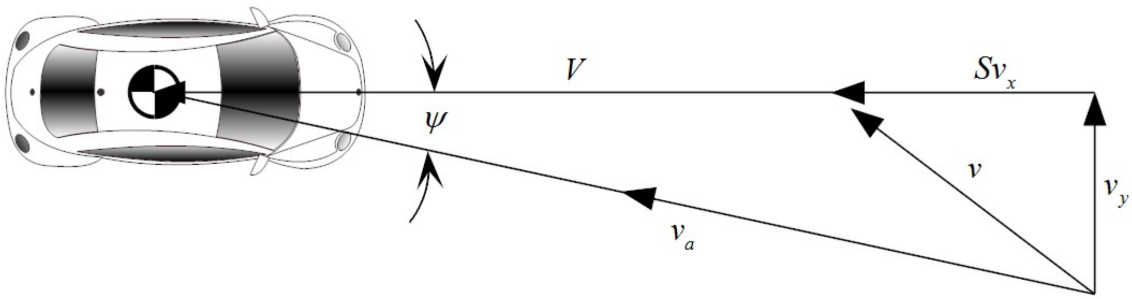


Figure 7.2 Total airspeed is the vector sum of car speed and wind speed, both relative to ground

The drag coefficient $C_D{}'$ is the sum of the drag coefficient at zero yaw (C_D) and a coefficient k times the square of the sine of the yaw angle, ψ for a typical passenger car.

$$C_D{}' = C_D + k\sin^2\psi \tag{7.8}$$

where:

$$\sin\psi = \frac{v_y}{\sqrt{(V+Sv_x)^2+v_y^2}} \tag{7.9}$$

Therefore Equation (7.8) becomes:

$$C_D{}' = C_D + k\frac{v_y^2}{(V+Sv_x)^2+v_y^2} \tag{7.10}$$

Aerodynamic drag force can be written by inserting Equations (7.7) and (7.10) into Equation (7.2).

$$F_D = \underbrace{\left[C_D + k\frac{v_y^2}{(V+Sv_x)^2+v_y^2}\right]}_{C_X} A \underbrace{\left[\frac{\rho\left[(V+Sv_x)^2+v_y^2\right]}{2}\right]}_{q} \tag{7.11}$$

Equation (7.11) can be simplified as it is shown below:

$$F_D = C_D \times A\left[\frac{\rho\left[\left(V+Sv_x\right)^2+v_y^2\right]}{2}\right]+\left[k\frac{v_y^2}{\left(V+Sv_x\right)^2+v_y^2}\right]\times A\left[\frac{\rho\left[\left(V+Sv_x\right)^2+v_y^2\right]}{2}\right] \tag{7.12}$$

$$F_D = C_D \times A\left[\frac{\rho\left[\left(V+Sv_x\right)^2+v_y^2\right]}{2}\right]+ \left[k\frac{v_y^2}{\cancel{\left(V+Sv_x\right)^2+v_y^2}}\right]\times A\left[\frac{\rho\cancel{\left[\left(V+Sv_x\right)^2+v_y^2\right]}}{2}\right] \tag{7.13}$$

$$F_D = C_D \times A\left[\frac{\rho\left[\left(V+Sv_x\right)^2+v_y^2\right]}{2}\right]+\left[kv_y^2\right]\times A\left[\frac{\rho}{2}\right] \tag{7.14}$$

$$F_D = \frac{1}{2}\rho C_D A\left[\left(V+Sv_x\right)^2+v_y^2\right]+\frac{1}{2}\rho k A v_y^2 \tag{7.15}$$

Further simplification can be done to Equation (7.15) by factoring and unwrapping the first square term on the right hand side.

$$F_D = \frac{1}{2}\rho\left(C_D+k\right)Av_y^2+\frac{1}{2}\rho C_D A\underbrace{\left(V+Sv_x\right)^2}_{V^2+2VSv_x+v_x^2} \tag{7.16}$$

The term linear in V is ignored. The error introduced by ignoring this term (and the road grade) is minimized by the averaging process subsequently applied because these terms change sign for each change in coastdown direction.

Collecting terms, Equation (7.16) can be rewritten as:

$$F_D = \frac{1}{2}\rho C_D A\left(V^2+v_x^2\right)+\frac{1}{2}\rho\left(C_D+k\right)Av_y^2 \tag{7.17}$$

A similar analysis can be applied to formulate lift and side forces, however the change in altitude is small and road that coastdown test is held is straight, and the effect of lift and side forces will be neglected.

7.2.2 Tire and Chassis Drag

A detailed analysis of all the forces, torques, and inertias on a vehicle chassis is beyond the scope of this study. However, the total force can be expected to vary as a function of air temperature, road temperature, ground speed, normal load, and lateral load.

In the absence of slip angles, tire rolling resistance, F_R can be expected to increase with speed. Although this increase is often considered to be linear at normal speeds, a second degree function will fit well in the speed range of a coastdown test, as seen in Figure 7.3.

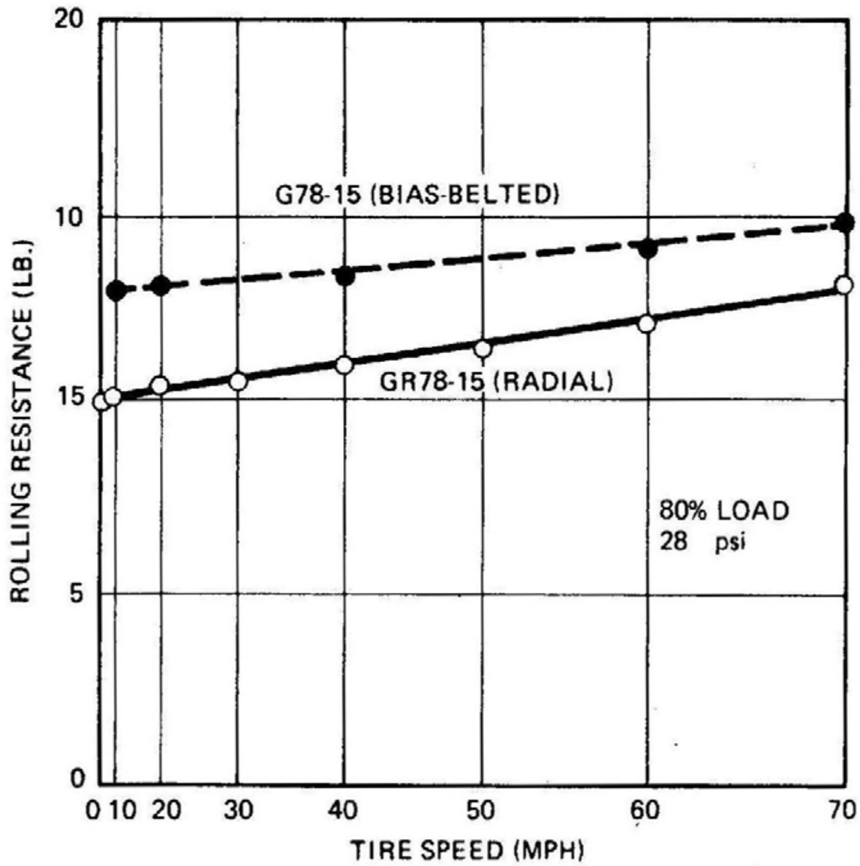


Figure 7.3 Tire rolling resistance increases linearly with the square of speed.[26]

Tire rolling resistance is defined as coefficient of rolling resistance, μ, times vehicle test weight W.

$$F_R = \mu W \tag{7.18}$$

where:

$$\mu = \mu_0 \left(1 + \mu' V^2\right) \tag{7.19}$$

Equation (7.19) describes the relationship, with μ_0 designating the extrapolation of rolling resistance to zero speed, and μ' describing the rate of change of rolling

[26] T. P. Yasin

resistance with the square of vehicle ground speed. In other words, μ_0 is the velocity independent coefficient of rolling resistance and μ' is the velocity coefficient of rolling resistance.

Hence, tire rolling resistance can be written in the absence of aerodynamic lift forces and lateral force effects as:

$$F_R = \mu_0 \left(1 + \mu' V^2\right) W \tag{7.20}$$

7.2.3 Mathematical Solution to Road Load Force

Road load force can be formulated by inserting Equations (7.17) and (7.20) into Equation (7.1):

$$F_{RL} = \frac{1}{2}\rho C_D A\left(V^2 + v_x^2\right) + \frac{1}{2}\rho\left(C_D + k\right) A v_y^2 + \mu_0\left(1 + \mu' V^2\right) W \tag{7.21}$$

Road load force can be expressed as rate of change of vehicle speed times effective mass of the vehicle:

$$F_{RL} = -M_e \frac{dV}{dt} \tag{7.22}$$

Therefore:

$$-M_e \frac{dV}{dt} = \frac{1}{2}\rho C_D A\left(V^2 + v_x^2\right) + \frac{1}{2}\rho\left(C_D + k\right) A v_y^2 + \mu_0\left(1 + \mu' V^2\right) W \tag{7.23}$$

Collecting terms, Equation (7.23) can be rewritten as:

$$-M_e \frac{dV}{dt} = f_0 + f_2 V^2 \tag{7.24}$$

where:

$$f_0 = \mu_0 W + \left(f_2 - \mu_0 \mu' W\right) v_x^2 + \frac{1}{2}\rho C_{DY} A v_y^2 \tag{7.25}$$

$$f_2 = \mu_0 \mu' W + \frac{1}{2}\rho C_D A \tag{7.26}$$

The crosswind aerodynamic drag coefficient C_{DY} is a measure of the response of the vehicle to the crosswind component of the wind at small yaw angles. It may be calculated by:

$$C_{DY} = C_D + k \tag{7.27}$$

Equation (7.24) will be resembled to following integral to apply its solution to road load force equation:

$$\int -\frac{dx}{a+bx^2} = -\frac{\tan^{-1}\left(\frac{\sqrt{b}x}{\sqrt{a}}\right)}{\sqrt{a}\sqrt{b}} \tag{7.28}$$

where Equation (7.24) can be written as:

$$-\frac{dV}{\underbrace{\frac{f_0}{M_e}}_{a}+\underbrace{\frac{f_2}{M_e}}_{b}V^2} = dt \tag{7.29}$$

Integrating both sides will give the right hand solution of the Equation (7.28). Similarly, one can write:

$$-\frac{\tan^{-1}\left(\frac{\sqrt{\frac{f_2}{M_e}}V}{\sqrt{\frac{f_0}{M_e}}}\right)}{\sqrt{\frac{f_0}{M_e}}\sqrt{\frac{f_2}{M_e}}} = t + constant \tag{7.30}$$

Effective mass terms at nominator can be cancelled and denominator effective mass term can be factored out as follows:

$$-\frac{\tan^{-1}\left(\frac{\sqrt{\frac{f_2}{\cancel{M_e}}}V}{\sqrt{\frac{f_0}{\cancel{M_e}}}}\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} = t + constant \tag{7.31}$$

One can get the following expression to apply boundary conditions and determine $constant$.

$$-\frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} = t + constant \tag{7.32}$$

Boundary conditions can be specified as:

$$V(t_0) = V_0 \tag{7.33}$$

$$V(t) = V \tag{7.34}$$

V_0 is the initial speed at start of the coastdown test and t_0 is the start time which is simply zero.

Apply first boundary condition to Equation (7.32):

$$-\frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} = t_0 + constant \tag{7.35}$$

And $constant$ can be expressed as:

$$constant = -\frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} - t_0 \tag{7.36}$$

Insert $constant$ term back into Equation (7.32) to obtain vehicle speed and time relationship for an arbitrary time as specified in second boundary condition with Equation (7.34).

$$-\frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} = t - \frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} - t_0 \tag{7.37}$$

Arrange terms to get:

$$t - t_0 = \frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V_0\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} - \frac{\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V\right)}{\frac{\sqrt{f_0 f_2}}{M_e}} \tag{7.38}$$

By factoring terms, one gets:

$$t - t_0 = \frac{M_e}{\sqrt{f_0 f_2}}\left[\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V_0\right) - \tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V\right)\right] \tag{7.39}$$

This is the equation which, after correction of the coefficients determined by the White and Korst technique or equivalent, is used to calculate the coastdown time interval. The units for M_e, f_0, f_2, V, and V_0 must be chosen so that the argument of the inverse tangent function is dimensionless and the resultant coastdown time is in seconds. The individual terms and their corrections are described in the 7.4 Data Correction.

After this point, one can nondimensionalize Equation (7.39) and follow White and Korst technique or keep the equation with these parameters and write it as speed as a function of time instead of time as a function of speed as it is in Equation (7.39).

Result wise there is not any difference between nondimensionalizing and keeping dimensional parameters. Only difference comes when writing program codes for the solution. Nondimensionalize solution requires changing input from vehicle speed versus time to nondimensionalized vehicle speed and time. On the other hand in dimensional approach, vehicle speed versus time data is supplied as they are obtained from coastdown tests. For simplicity parametric approach is followed in this study and following steps taken to get vehicle speed as a function of time from Equation (7.39).

$$\frac{\sqrt{f_0 f_2}}{M_e}\left(t - t_0\right) = \tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V_0\right) - \tan^{-1}\left(\sqrt{\frac{f_2}{f_0}} V\right) \tag{7.40}$$

$$\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V\right)=\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)-\frac{\sqrt{f_0 f_2}}{M_e}(t-t_0) \tag{7.41}$$

Take tangents of both sides:

$$\sqrt{\frac{f_2}{f_0}}V=\tan\left[\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)-\frac{\sqrt{f_0 f_2}}{M_e}(t-t_0)\right] \tag{7.42}$$

$$V=\sqrt{\frac{f_0}{f_2}}\tan\left[\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right)-\frac{\sqrt{f_0 f_2}}{M_e}(t-t_0)\right] \tag{7.43}$$

Applying the method of least squares to Equation (7.43) for determining optimal values of f_0 and f_2 requires that

$$\frac{\partial}{\partial f_0}\sum\left[V_i-V\left(f_0,f_2,t_i\right)\right]^2=0 \tag{7.44}$$

$$\frac{\partial}{\partial f_2}\sum\left[V_i-V\left(f_0,f_2,t_i\right)\right]^2=0 \tag{7.45}$$

Mathematical solution to these equalities is carried out via MATLAB and written code is represented at Appendix E: Coastdown Coefficient Calculation MATLAB Code.

7.2.4 Effective Vehicle Mass

The effective vehicle mass M_e is the sum of the final vehicle test mass $\left(M = W/g\right)$ and the effective mass of the rotating components. The effective mass of the drivetrain components other than the wheels, tires, and brakes may be ignored. For each tire, wheel, and brake rotor or drum, the effective mass, m_e is:

$$m_e=\frac{I}{r^2} \tag{7.46}$$

where:

r is the rolling radius of the tire and I is the polar moment of inertia of the assembly. The polar moment of inertia may be measured or may be estimated circular disk expression:

$$I = \frac{W_w}{g}\frac{r^2}{2} \tag{7.47}$$

where:

W_w is the weight of the tire, wheel, and brake rotor or drum. If no measurements are available, the effective inertia of all the rotating components may be estimated 3.0% of the vehicle test mass.

$$M_e = 1.03\frac{W}{g} = 1.03M \tag{7.48}$$

Or, one can insert Equation (7.47) to Equation (7.46) and obtain:

$$m_e = \frac{\frac{W_w}{g}\frac{\cancel{r^2}}{2}}{\cancel{r^2}} \tag{7.49}$$

$$m_e = \frac{W_w}{2g} \tag{7.50}$$

Therefore one can find effective vehicle mass, M_e by adding effective masses of tire, wheel, and brake rotor or drum, m_e to vehicle mass M .

$$M_e = M + \sum m_e \tag{7.51}$$

By inserting Equation (7.50) following effective vehicle mass is obtained to use in Equation (7.43) while solving for f_0, and f_2.

$$M_e = M + \sum \frac{W_w}{2g} \tag{7.52}$$

7.3 DATA ACCEPTABILITY CRITERIA

Experience has shown that the criteria of this section are necessary and sufficient to provide accurate and precise test results. Data which exceed these criteria generally arise from wind gusts or driver inputs, which violate the assumption that the forces on vehicle are depicted by the following equation:

$$-M_e\frac{dV}{dt} = f_0 + f_2V^2 \tag{7.53}$$

7.3.1 Criteria 1

a) Analyze each individual coastdown $V(t)$ in the set of paired runs by White & Korst method to obtain the coefficients f_0 and f_2.

b) Compare each individual $V(t)$ trace and its analytical counterpart $V(f_0, f_2, t)$ by using:

$$t - t_0 = \frac{M_e}{\sqrt{f_0 f_2}}\left[\tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V_0\right) - \tan^{-1}\left(\sqrt{\frac{f_2}{f_0}}V\right)\right] \tag{7.54}$$

- If the root mean square deviation (RMSD) exceeds $0.25\,mph$ on any individual run, discard that run and the paired run in the opposite direction.
- If less than three pairs comply with this criterion, the test run is invalid.

7.3.2 Criteria 2

Of the paired runs meeting the first criteria, those which fail to satisfy the following criteria regarding f_0 and f_2 must also be discarded.

a) The standard deviation of the f_0's must be less than $2.5\,lb$ or 5% of the mean. If this value is exceeded, discard the run and its pair with f_0 farthest from mean and recompute the standard deviation until compliance is obtained or until the remaining pairs number less than three.

b) The standard deviation of the f_2's must be less than $0.001\,lb/mph^2$ or 3% of the mean. If this value is exceeded, discard the run and its pair with f_2 farthest from the mean and recompute the standard deviation until compliance is obtained or until the remaining pairs number less than three.

7.3.3 Result

- If less than three pairs remain, the test run is invalid.
- Average f_0's and f_2's of all remaining runs to determine a f_0 and f_2.

7.4 DATA CORRECTION

The average f_0 and f_2 values must now be corrected to a standard set of ambient conditions. The standard conditions are:

- Temperature $68\ ^0F$
- Atmospheric pressure $29.00\ in-Hg$
- Zero wind
- The effect of humidity on air density may be ignored

7.4.1 Wind Correction to f_0

$$f_0 = \mu_0 W + \left(f_2 - \mu_0 \mu' W \right) v_x^2 + \frac{1}{2} \rho C_{DY} A v_y^2 \tag{7.55}$$

Separate the rolling resistance from wind effects as follows:

$$\mu_0 W = \frac{f_0 - f_2 v_x^2 - \frac{1}{2} \rho C_{DY} A v_y^2}{1 - \mu' v_x^2} \tag{7.56}$$

where:

$\rho =$ Mass density of ambient air

$\mu' =$ Velocity coefficient of rolling resistance

$C_{DY} =$ Crosswind aerodynamic drag coefficient

$v_x =$ Component of wind parallel to track

$v_y =$ Component of wind perpendicular to the track

Unless specific information about the test vehicle is available, use the following values for the coefficients:

$$\begin{aligned} \mu' &= 50 \times 10^{-6} \frac{1}{(mph)^2} \\ C_{DY} &= 3.4 \frac{\left(ft/s \right)^2}{(mph)^2} \end{aligned} \tag{7.57}$$

7.4.2 Temperature Correction to f_0

The temperature dependence of rolling resistance shall be corrected by:

$$f_0' = \mu_0 W\left[1 + k_t\left(T - T_0\right)\right] \tag{7.58}$$

Unless specific information about the test vehicle is available, use:

$$k_t = 4.8\times10^{-3}\,\tfrac{1}{^\circ F} \tag{7.59}$$

- Significant changes in sun load may affect rolling resistance and, consequently, contribute to test variations.

7.4.3 Air Density Correction to f_2

Adjust the coefficient of the V^2 term to standard ambient conditions $\left(\rho_{air} = 0.002266\,slugs/ft^3\right)$ by the equation:

$$f_2' = \left(\frac{P_0 T}{P T_0}\right)\left[f_2 - \mu'\left(\mu_0 W\right)\right] + \mu' f_0' \tag{7.60}$$

Where:

P = Barometric pressure

P_0 = $29.00\ in-Hg$

T = Absolute temperature of the ambient air $\left(K \text{ or } {}^0R\right)$

T_0 = $293.16\ K\ (527.69\ {}^0R)$

Chapter 8 Engine and Vehicle Simulation Software Programs

8.1 OVERVIEW

In this chapter of the thesis software programs: AVL ADVISOR, CRUISE, and BOOST which will be used in future analysis of the heavy-duty vehicles are discussed. AVL ("Anstalt für Verbrennungskraftmaschinen" - Institute for Internal Combustion Engines) is the world's largest privately owned company for development of powertrains (combustion engines, hybrid systems, and electric drive) as well as simulation and test systems for passenger cars, trucks and marine engines.[27]

AVL ADVISOR and CRUISE are the vehicle simulation software programs, and BOOST is specialized in the engine simulation. While CRUISE is broader and much advanced vehicle simulation software, ADVISOR is much smaller and easy to use software compared to CRUISE however it runs on the MATLAB platform which means user needs to have MATLAB installed in his computer to use ADVISOR. However, CRUISE and BOOST are standalone applications and they can connect to each other for a co-simulation like CRUISE using a BOOST engine.

8.2 AVL ADVISOR[28]

A trial version of the AVL ADVISOR was tested to understand its capabilities and user options. Advisor is a MATLAB based vehicle simulation program and it is integrated into the MATLAB with special blocks and a user interface as shown in Figure 1 to control and communicate with the SIMULINK models. As can be seen from the

[27] http://www.avl.com/wo/webobsession.servlet.go?app=bcms&page=view&nodeid=400013015
[28] AVL ADVISOR User Guide

Figure 8.1, ADVISOR is capable of doing calculations in both metric and US unit system.

Figure 8.1 Advisor Opening Snapshot

Start button takes you to the input screen as seen below in Figure 8.2. Standard vehicle and corresponding default values can be seen in the figure.

Previously saved vehicle models can be loaded or vehicle models can be generated by using input screen. Drivetrain configuration can be set and by changing that Vehicle Input picture is changing. Vehicle Input picture is a dynamic picture which you can change the part properties by clicking on them. Moreover you have access to individual drivetrain m-file which can be manipulated through a pop-up window. These m-files generally contain the energy loss characteristics of that drivetrain unit i.e. torque-efficiency map.

After selecting all desired components of the vehicle, scalar input variables can be modified one by one by using the variable list editing located below of the input screen.

Auto-Size option on the top right is used adjust vehicle parameters of the vehicle until it meets acceleration and gradeability goals. The default performance targets are maintaining at least a 6% grade at 55 *mph*, and obtaining less than 12 seconds 0-60 *mph* time, 23.4 seconds 0-85 *mph* time, and 5.3 seconds 40-60 *mph*.

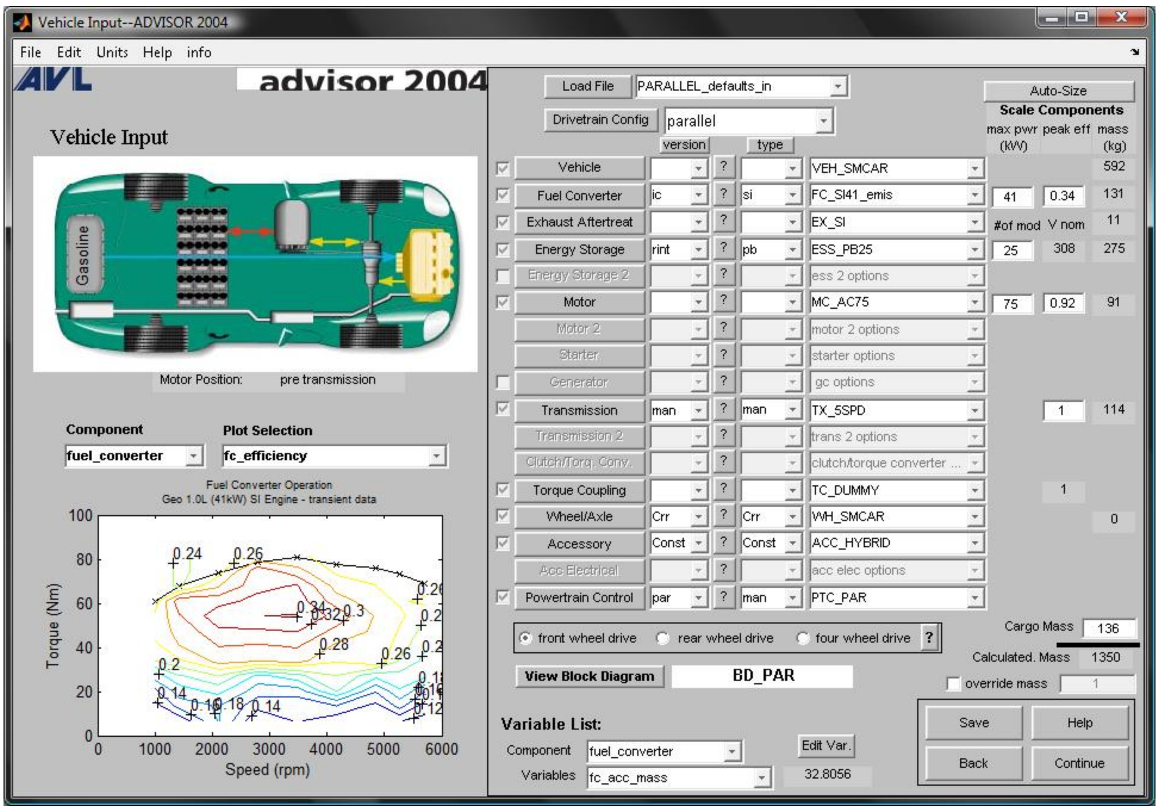


Figure 8.2 Vehicle Input Screen

With continue button we come to simulation parameters figure as shown in Figure 8.2. Simulation parameters setup gives you several options on how to test the currently defined vehicle. Pre-defined drive cycles can be loaded or an individual drive cycle can be built by trip builder. Time steps and the number of cycles that is going to be repeated can be set in this part also.

In addition to standard tests, acceleration and grade tests can also be applied independently. Moreover by multiple cycles up to eight drive cycles can be tested simultaneously. Standard test procedures i.e. SAE J1711, Real World, City Highway, TEST FTP and TEST FTP HYBRID, can be applied to the vehicle if this option is selected.

Auxiliary electric loads can be taken into account by activating them through the checkbox located at the bottom of the parameter page. On-off times and characteristic power usages of these units can be set through the opened auxiliary load page.

To see the effect that up to three variables have on the vehicle, select a parametric study. The low and high values may be set, as well as the number of points desired for that variable. A parametric study runs a set of simulations to cover the matrix of input points, such that if 3 variables are selected with 3 points each, 27 simulations will run. If the Save Runs checkbox is selected, each of the individual runs will be saved with a naming convention of Prefix_Factor1Level#_Factor2Level#_Factor3Level#.mat. The saved results can be analyzed by loading them into the results figure or the compare simulation window.

When Run DOE under Options menu is selected, a new window will appear to guide the user through the process of running a statistical design of experiments. The DOE feature allows the user to specify as many factors and levels as desired which is an expansion of the parametric study feature.

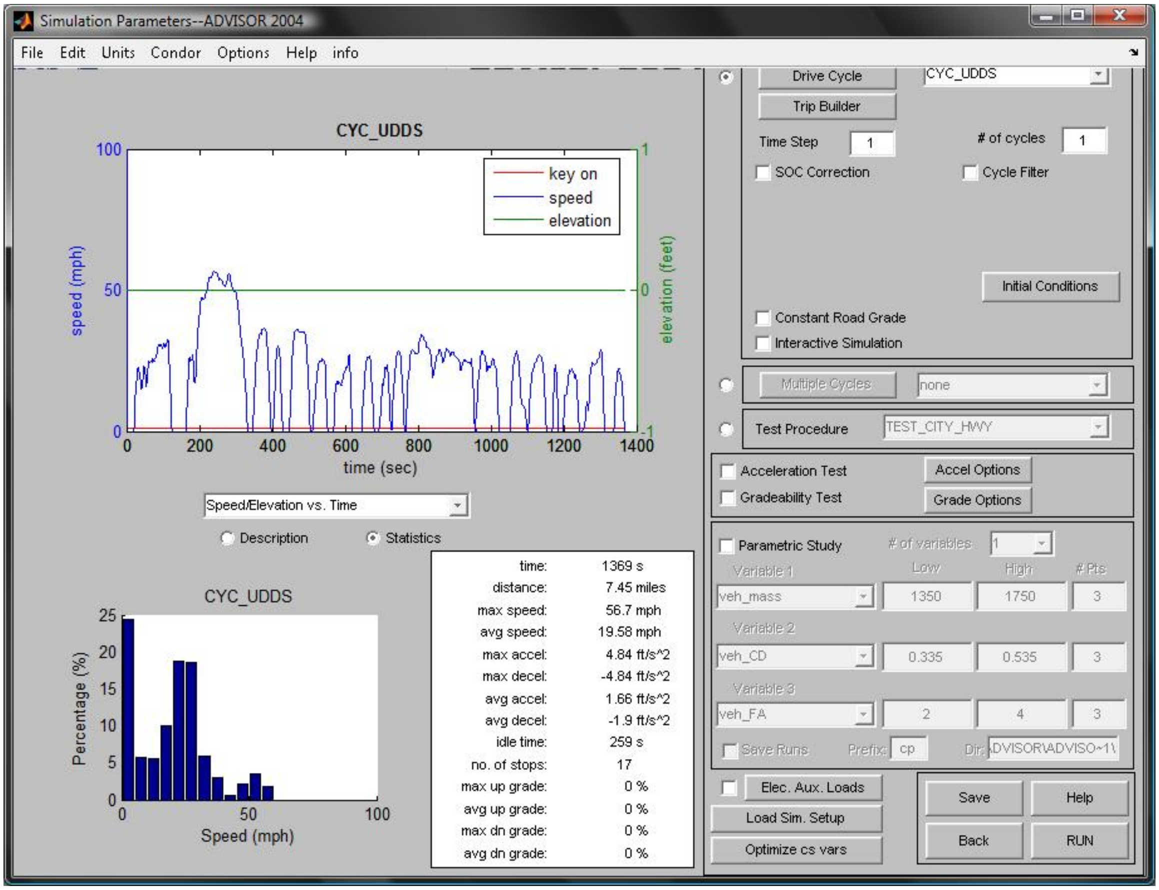


Figure 8.3 Simulation Parameters Screen

The results figure presents some summary results (fuel economy, emissions, total distance, etc.) and allows the user to plot up to four time series plots by selecting a variable from the popup menu. If the acceleration and gradeability checkboxes were picked in the simulation setup screen, appropriate results will also be displayed. An emission test results will be presented as a standard also but extensive analysis options are not available in the program.

By clicking the Energy Use Figure button, a new figure is opened showing how energy was used and transferred for the vehicle during the simulation. The Output Check

Plots button pulls up plots that show the vehicle's performance, some of which are not available under the time series plots.

Figure 8.4 Results Screen

Apart from this portion of the program there is the MATLAB portion of the ADVISOR. To make an extensive analysis and to explore the capabilities of the ADVISOR this portion will be analyzed also.

8.3 AVL CRUISE[29]

CRUISE is a software for simulating driving performance, fuel consumption and emissions. Its modular concept enables free modeling of all possible vehicle configurations while sophisticated solvers guarantee short calculation times.

CRUISE is typically used in drive train and engine development to calculate and optimize the following:

- Fuel Consumption and Emissions
- Driving Performance (acceleration, elasticity)
- Transmission Ratios
- Braking Performance

and for the determination of:

- Collective Loads for Stress Calculations
- Drivetrain Vibrations

The modular structure of CRUISE permits modeling of all existing and future vehicle concepts for both single and double track vehicles (motorcycles, passenger cars, trucks, etc.).

8.4 AVL BOOST[30]

BOOST simulates a wide variety of engines, 4-stroke or 2-stroke, spark or auto-ignited. Applications range from small capacity engines for motorcycles or industrial purposes up to large engines for marine propulsion. BOOST can also be used to simulate the characteristics of pneumatic systems.

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[29] AVL CRUISE User Guide
[30] AVL BOOST User Guide

The BOOST program package consists of an interactive pre-processor which assists with the preparation of the input data for the main calculation program. Results analysis is supported by an interactive post-processor.

The pre-processing tool of the AVL Workspace Graphical User Interface features a model editor and a guided input of the required data. The calculation model of the engine is designed by selecting the required elements from a displayed element tree by mouse-click and connecting them by pipe elements. In this manner even very complex engine configurations can be modeled easily, as a large variety of elements is available.

The main program provides optimized simulation algorithms for all available elements. The flow in the pipes is treated as one-dimensional. This means that the pressures, temperatures and flow velocities obtained from the solution of the gas dynamic equations represent mean values over the cross-section of the pipes. Flow losses due to three-dimensional effects, at particular locations in the engine, are considered by appropriate flow coefficients. In cases where three-dimensional effects need to be considered in more detail, a link to AVL's three-dimensional flow simulation code FIRE is available. This means that a multi-dimensional simulation of the flow in critical engine parts can be combined with a fast one-dimensional simulation elsewhere. This feature could be of particular interest for the simulation of the charge motion in the cylinder, the scavenging process of a two-stroke engine or for the simulation of the flow in complicated muffler elements.

Chapter 9 Conclusions and Recommendations for Future Research

"Fuel Economy Modeling of Light-Duty and Heavy-Duty Vehicles and Coastdown Study" thesis is product of the one and a half year research for the Texas Department of Transportation's (TxDOT's) "Estimating Texas Vehicle Operating Costs" project. The goal of the TxDOT project is to estimate vehicle operating costs for the fleets of the vehicles including broad range of vehicles class i.e. light- to heavy-duty vehicles. Vehicle operating costs (Vcost) play an important role in several TxDOT policy making areas ranging from the economic evaluation of highway construction, maintenance, and rehabilitation strategies to lane rental, liquidated damages and construction bonus calculations. Vcost relationships have not been studied in Texas for over two decades and these now risk obsolescence in the face of new design technologies, engine changes – both hybrid and improved gasoline/diesel – better tire performance.[31]

Fuel cost is the dominant cost in vehicle operating costs with 35%. With the increasing oil prices and carbon dioxide emissions of the automobiles fuel economy's importance is high in recent years with increase in awareness of the consumers.

Fuel estimation took an experimental format until the mid 1980s when alternative modeling offered more flexible ways of estimating consumption. Mechanistic models incorporates changes in engine design, body style and tire technology developments which results in a dynamic fuel economy model and it is independent of region. Moreover, different types of fuels can be easily adapted to the model and their effects on the fuel consumption can be analyzed.

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[31] TxDOT Project No. 0-5974 Proposal

Fuel economy model for class of vehicles aim is to calculate a fleet fuel economy for different compositions of the fleets. This is very useful for big enterprises who own wide range of vehicles from light- to heavy-duty vehicles. Effect of setting a speed limit of 65 *mph* instead of 64 *mph* can be analyzed easily and effect of increasing speed in delivery times and its effect on company profit can be analyzed. While putting this model together EPA's data is used to get enough vehicles in each class for years 2000 till 2008. A database needs to be created for the software for adding every coming year and the software should be able to convert the data according to its needs.

Road load force analysis that was done on the EPA's Annual Certification Data revealed that classes of the vehicles specified by the EPA has some uncertainty as it was shown with Ferrari 612 Scaglietti as medium class vehicle. It is also noticed that the world does not have a single standard about vehicle classes in LDV's.

On the other hand, vehicle specific approach uses the equations derived by Matthews, 2007. This model is purely mechanistic and its base is the power flow through vehicle systems and analysis of the losses on these systems. The road load force requirements again calculated by use of the coastdown coefficients derived from EPA's website and for heavy-duty vehicles these coefficients will be derived from the coastdown tests that were done at SH45 SE toll-road of Austin, TX before the road was opened to the public on May 1, 2009. The software developed for the vehicle specific approach needs to be developed more by a better indicated thermal efficiency model. Effects of engine efficiencies on fuel economy are analyzed and it is observed that indicated thermal efficiency plays an important role in gear changes. Indicated thermal efficiency model will be updated by Woschni's[32] heat transfer model for the internal combustion engines. A user's manual needs to be written for the software updates for the future researchers who wants to update the model. Effects of tires on the fuel consumption need to be analyzed for better fuel economy model. It is known that Bridgestone has a computer model to analyze the effects of the different tires including other brands. Some effort is put to get access to this software however it was not successful. A broader literature search needs to be done for this subject.

Hybrid vehicles analyzed only in the class based approach of the fuel economy in Chapter 4 however, vehicle specific approach is not capable of analyzing the hybrid vehicles. The number of the hybrid vehicles on the roads is increasing in the US extensively with the rise of gasoline pump prices, thus more attention should be given to hybrids. Newly, hybrid heavy-duty vehicles are also available in the market. AVL Advisor software is capable of analyzing the hybrid vehicles including serial and parallel hybrid configurations, therefore; AVL Advisor can be a benchmark and a starting point for future analysis.

An AVL Cruise and Boost co-simulation will be used for heavy-duty vehicle fuel economy model.[33] This model will be very important for the future studies related with the fuel economy since it needs close analysis of the each vehicle component. Thus effect of the components on the fuel consumption will be analyzed more accurately.

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[32] G. Woschni

[33] Regner, G., E. Loibner, J. Krammer, L. Walter, and R. Truemner

Appendix A: Road Load Force Calculation MATLAB Code

```
clear
clc

fprintf ('Input year: \n');
year = input('Specify year from 2000 to 2008 \n');

[num, txt] = xlsread('2008-2000 all data.xlsx', num2str(year));
mkdir(['LDV Figures\',num2str(year)])

% Make A,B,C zero to handle empty cell problem.
A = zeros(length(num),1);
B = zeros(length(num),1);
C = zeros(length(num),1);

A = num(:,17);
B = num(:,18);
C = num(:,19);

class = txt(:,1);
trans = txt(:,3);
division = txt(:,10);
carline = txt(:,12);


j = 1;
for i=2:(length(A)-1)
    if strcmp(class(i), class(i+1)) ~= 1
        N(j) = i-1;
        j = j + 1;
    end

end

x = length (N);
N(x+1) = length (A);

S=0:60;

i = 1;
j = 1;
m = 1;
k = 1;
```

```
r = 1;
t = 1;

for m=1 :length (N)

    %     Empty cells which are holding data in while loop
    M = zeros (1,1);
    Auto = zeros(1,1);
    Manual = zeros(1,1);
    Name = cellstr('');
    AutoName = cellstr('');
    ManualName = cellstr('');
    checkAuto = 0;
    checkManual = 0;

    z = 1;
    r = 1;
    t = 1;


    while (i <= N(j))
        for k=1 : length(S)
            M(z,k)=A(i)+B(i)*S(k)+C(i)*S(k)^2;

            % Automatic and manual transmission differentiation
            if strcmp(trans(i+1), 'A') == 1
                Auto(r,k) = M(z,k);
                checkAuto = 1;
            else
                Manual(t,k) = M(z,k);
                checkManual = 1;
            end
        end

        Name(z) = cellstr([char(division(i+1)), ' - ',
char(carline(i+1))]);

        if strcmp(trans(i+1), 'A') == 1
            AutoName(r) = cellstr([char(division(i+1)), ' - ',
char(carline(i+1))]);
            r = r+1;
        else
            ManualName(t) = cellstr([char(division(i+1)), ' - ',
char(carline(i+1))]);
            t = t+1;
        end

        i = i+1;
```

```
        z = z+1;

    end


    %
************************************************************************
*
    %
************************************************************************
*
    %
************************************************************************
*
    %
************************************************************************
*


    %
    %
    % FIGURE OF CLASS (AUTO & MANUAL)
    %
    %

    figure(3*m-2);

    [row,col] = size(M);

    if row == col
        plot(S, M', 'DisplayName', Name, 'XDataSource', 'S',
'YDataSource','M'); figure(gcf);
    else
        plot(S, M, 'DisplayName', Name, 'XDataSource', 'S',
'YDataSource','M'); figure(gcf);
    end

    hold on;
    xlabel('Speed [mph]');
    ylabel('F_R _L (Road Load Force) [lbf]');
    title([char(class(i)), ' - ', num2str(year)]);
    grid on;

    if row ~= 1

        M_max = max (M);
        M_min = min (M);
        M_avg = mean (M);
```

```
        h(1) = plot(S, M_max, '-.or', 'DisplayName', '(F_R_L) _m_a_x',
'XDataSource', 'S', 'YDataSource', 'M_max'); figure(gcf);
        h(2) = plot(S, M_min, '-.ob', 'DisplayName', '(F_R_L) _m_i_n',
'XDataSource', 'S', 'YDataSource', 'M_min'); figure(gcf);
        h(3) = plot(S, M_avg, '-.vk', 'DisplayName', '(F_R_L) _a_v_g',
'XDataSource', 'S', 'YDataSource', 'M_avg'); figure(gcf);

        legend(h, 'Location', 'NorthWest');

    end

    for d = 1 : (z-1)
        if M(d,:) == M_max

            text('String',[char(Name(d)), ' \rightarrow   '],...
                'Position',[S(50),M(d,50)],...
                'HorizontalAlignment','right', 'FontWeight', 'bold');
        end

        if M(d,:) == M_min

            text('String',['   \leftarrow ', char(Name(d))],...
                'Position',[S(27),M(d,25)],...
                'HorizontalAlignment','left', 'FontWeight', 'bold');
        end
    end

    hold off;

    %
*****************************************************************
    %     Printing
    %
*****************************************************************


    orient landscape;
    %     print -P\\ENGR-Print1\ENGR-SC2-Laser-1;
    %     print -PTFS;



    %
*****************************************************************
    %     Saving
    %
*****************************************************************
```

```
    saveas(gcf,['LDV Figures\', num2str(year), '\', char(class(i)), ' -
', num2str(year)],'fig')
    set(gcf, 'Visible', 'off');



    %
************************************************************************
*
    %
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*
    %
************************************************************************
*

    %
    %
    % FIGURE OF AUTOMATIC TRANSMISSION CLASS
    %
    %
    if checkAuto

        figure(3*m-1);

        [row,col] = size(Auto);

        if row == col
            plot(S, Auto', 'DisplayName', AutoName, 'XDataSource', 'S',
'YDataSource','Auto'); figure(gcf);
        else
            plot(S, Auto, 'DisplayName', AutoName, 'XDataSource', 'S',
'YDataSource','Auto'); figure(gcf);
        end

        hold on;
        xlabel('Speed [mph]');
        ylabel('F_R _L (Road Load Force) [lbf]');
        title([char(class(i)), ' - ', num2str(year), ' (Automatic)']);
        grid on;

        if row ~= 1

            Auto_max = max (Auto);
            Auto_min = min (Auto);
```

```
            Auto_avg = mean (Auto);

            h(1) = plot(S, Auto_max, '-.or', 'DisplayName', '(F_R_L)
_m_a_x', 'XDataSource', 'S', 'YDataSource', 'Auto_max'); figure(gcf);
            h(2) = plot(S, Auto_min, '-.ob', 'DisplayName', '(F_R_L)
_m_i_n', 'XDataSource', 'S', 'YDataSource', 'Auto_min'); figure(gcf);
            h(3) = plot(S, Auto_avg, '-.vk', 'DisplayName', '(F_R_L)
_a_v_g', 'XDataSource', 'S', 'YDataSource', 'Auto_avg'); figure(gcf);

            legend(h, 'Location', 'NorthWest');

        end

        for d = 1 : (r-1)
            if Auto(d,:) == Auto_max

                text('String',[char(AutoName(d)), ' \rightarrow
'],...
                    'Position',[S(50),Auto(d,50)],...
                    'HorizontalAlignment','right', 'FontWeight',
'bold');
            end

            if Auto(d,:) == Auto_min

                text('String',['   \leftarrow ', char(AutoName(d))],...
                    'Position',[S(27),Auto(d,25)],...
                    'HorizontalAlignment','left', 'FontWeight',
'bold');
            end
        end

        hold off;

        %
*****************************************************************
        %     Printing
        %
*****************************************************************

        orient landscape;
        %     print -P\\ENGR-Print1\ENGR-SC2-Laser-1;
        %     print -PTFS;



        %
*****************************************************************
        %     Saving
```

```
        %
******************************************************************

        saveas(gcf,['LDV Figures\', num2str(year), '\', char(class(i)),
' - ', num2str(year), ' (Automatic)'],'fig')
        set(gcf, 'Visible', 'off');

    end

    %
************************************************************************
*
    %
************************************************************************
*
    %
************************************************************************
*
    %
************************************************************************
*

    %
    %
    % FIGURE OF MANUAL TRANSMISSION CLASS
    %
    %
    if checkManual

        figure(3*m);

        [row,col] = size(Manual);

        if row == col
            plot(S, Manual', 'DisplayName', ManualName, 'XDataSource',
'S', 'YDataSource','Manual'); figure(gcf);
        else
            plot(S, Manual, 'DisplayName', ManualName, 'XDataSource',
'S', 'YDataSource','Manual'); figure(gcf);
        end

        hold on;
        xlabel('Speed [mph]');
        ylabel('F_R _L (Road Load Force) [lbf]');
        title([char(class(i)), ' - ', num2str(year), ' (Manual)']);
        grid on;

        if row ~= 1
```

```
            Manual_max = max (Manual);
            Manual_min = min (Manual);
            Manual_avg = mean (Manual);

            h(1) = plot(S, Manual_max, '-.or', 'DisplayName', '(F_R_L)
_m_a_x', 'XDataSource', 'S', 'YDataSource', 'Manual_max'); figure(gcf);
            h(2) = plot(S, Manual_min, '-.ob', 'DisplayName', '(F_R_L)
_m_i_n', 'XDataSource', 'S', 'YDataSource', 'Manual_min'); figure(gcf);
            h(3) = plot(S, Manual_avg, '-.vk', 'DisplayName', '(F_R_L)
_a_v_g', 'XDataSource', 'S', 'YDataSource', 'Manual_avg'); figure(gcf);

            legend(h, 'Location', 'NorthWest');

        end

        for d = 1 : (t-1)
            if Manual(d,:) == Manual_max

                text('String',[char(ManualName(d)), ' \rightarrow
'],...
                    'Position',[S(50),Manual(d,50)],...
                    'HorizontalAlignment','right', 'FontWeight',
'bold');
            end

            if Manual(d,:) == Manual_min

                text('String',['   \leftarrow ',
char(ManualName(d))],...
                    'Position',[S(27),Manual(d,25)],...
                    'HorizontalAlignment','left', 'FontWeight',
'bold');
            end
        end

        hold off;

        %
*****************************************************************
        %     Printing
        %
*****************************************************************

        orient landscape;
        %     print -P\\ENGR-Print1\ENGR-SC2-Laser-1;
        %     print -PTFS;
```

```
        %
*****************************************************************
        %     Saving
        %
*****************************************************************

        saveas(gcf,['LDV Figures\', num2str(year), '\', char(class(i)),
' - ', num2str(year), ' (Manual)'],'fig')
        set(gcf, 'Visible', 'off');
    end

    i = N(j) + 1;
    j = j + 1;
end
```

Appendix B: Overall Drivetrain Efficiency Calculation MATLAB Code

```
clear
clc

fprintf ('Input year: \n');
year = input('Specify year from 2000 to 2008 \n');

% READ VEHICLE DATA
[num, txt] = xlsread('Data v1.xlsx', num2str(year));

% Make A,B,C zero to handle empty cell problem.
A = zeros(length(num),1);
B = zeros(length(num),1);
C = zeros(length(num),1);
ETW = zeros(length(num),1);

displ = num(:,15);
ETW = num(:,17);
A = num(:,20);
B = num(:,21);
C = num(:,22);
fuel = num(:,28);

class = txt(:,1);
division = txt(:,11);
carline = txt(:,13);
trans = txt(:,17);

%  READ EPA'S FUEL ECONOMY DATABASE

%  Fuel Economy Database 1.xlsx : For year 2007 and before 2007
%  Fuel Economy Database 2.xlsx : For year 2008
%  Fuel Economy Database 3.xlsx : For TxDOT's data

if year == 2008
    [num, txt] = xlsread('Fuel Economy Database 2.xlsx',
num2str(year));
else
    [num, txt] = xlsread('Fuel Economy Database 1.xlsx',
num2str(year));
end
```

```
division2 = txt(:,2);
carline2 = txt(:,3);
trans2 = txt(:,6);
fuel2 = txt(:,14);

displ2 = num(:,1);
FE_City = num(:,8);
FE_Hway = num(:,9);


% READ COMPARISON DATABASE

% Manufacturer
[num, txt] = xlsread('Comparison Database.xlsx', 'Manufacturer');
division0 = txt(:,1);
division1 = txt(:,2);

% Carline
[num, txt] = xlsread('Comparison Database.xlsx', 'Carline');
carline0 = txt(:,2);
carline1 = txt(:,3);
carline_ = txt(:,4);    % Carline 1'in degisik versiyonu olursa

% Transmission
[num, txt] = xlsread('Comparison Database.xlsx', 'Transmission');
trans0 = txt(:,1);
trans1 = txt(:,2);

% Displacement
[num, txt] = xlsread('Comparison Database.xlsx', 'Displacement');
displ0 = num(:,1);
displ1 = num(:,2);

% Fuel Type
[num, txt] = xlsread('Comparison Database.xlsx', 'Fuel Type');
fuel0 = num(:,1);
fuel1 = txt(:,2);

% DENSITY & LHV
density_array = num(:,4);     % [kg/m^3]
LHV_array = num(:,5);         % [MJ/kg]


% READ FTP DATA
[num, txt] = xlsread('DDS.xlsx', 'FTP');

T_FTP = num(:,1);       % TIME (s)
S_FTP = num(:,2);       % SPEED (mph)
```

```
X_FTP = sum(S_FTP)/3600;

if year == 2008

    %  Split FTP into Bags

    T_Bag1 = num(1:506,1);
    T_Bag2 = num(506:1370,1);
    T_Bag3 = num(1370:1875,1);

    S_Bag1 = num(1:506,2);
    S_Bag2 = num(506:1370,2);
    S_Bag3 = num(1370:1875,2);

    X_Bag1 = sum(S_Bag1)/3600;
    X_Bag2 = sum(S_Bag2)/3600;
    X_Bag3 = sum(S_Bag3)/3600;

    % READ SC03 DATA
    [num, txt] = xlsread('DDS.xlsx', 'SC03');

    T_SC03 = num(:,1);       % TIME (s)
    S_SC03 = num(:,2);       % SPEED (mph)
    X_SC03 = sum(S_SC03)/3600;

    % READ US06 DATA
    [num, txt] = xlsread('DDS.xlsx', 'US06');

    T_US06 = num(:,1);       % TIME (s)
    S_US06 = num(:,2);       % SPEED (mph)
    X_US06 = sum(S_US06)/3600;

end

% READ HWFET DATA
[num, txt] = xlsread('DDS.xlsx', 'HWFET');

T_HWFET = num(:,1);       % TIME (s)
S_HWFET = num(:,2);       % SPEED (mph)
X_HWFET = sum(S_HWFET)/3600;

for i=1 :length (A)

    Manufacturer = Match(division(i+1), division0, division1, 1);
    [answer1, answer2] = Carline_Match(carline(i+1), carline0,
carline1, carline_);
    Transmission = Match(trans(i+1), trans0, trans1, 1);
```

```
    Displacement = Match(displ(i), displ0, displ1, 1);
    Fuel = Match(fuel(i), fuel0, fuel1, 0);

    [density, LHV] = Fuel_properties(fuel(i), fuel0, density_array,
LHV_array);

    for j=1 :length(FE_City)
        error = 0;
        if ( strcmp(answer1, carline2(j+1)) || strcmp(answer2,
carline2(j+1)) )
            if strcmp(Transmission, trans2(j+1))
                if Displacement == displ2(j)
                    if strcmp(Fuel, fuel2(j+1))
                        if strcmp(Manufacturer, division2(j+1))

                            x1(i,1) = FE_City(j);   % Find the
corresponding City FE
                            x2(i,1) = FE_Hway(j);   % Find the
corresponding Highway FE


                            if year == 2008

                                Bag1 = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_Bag1, S_Bag1, X_Bag1);
                                Bag2 = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_Bag2, S_Bag2, X_Bag2);
                                Bag3 = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_Bag3, S_Bag3, X_Bag3);
                                SC03 = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_SC03, S_SC03, X_SC03);
                                US06 = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_US06, S_US06, X_US06);
                                HWFET = FuelUsed2(ETW(i), A(i), B(i),
C(i), density, LHV, T_HWFET, S_HWFET, X_HWFET);

                                dummy_FE_City(i,1) = City_FE(Bag1,
Bag2, Bag3, SC03, US06);
                                City_eff(i,1) = x1(i,1) /
dummy_FE_City(i,1);

                                dummy_FE_Hway(i,1) = Hway_FE(Bag1,
Bag2, Bag3, SC03, US06, HWFET);
                                Hway_eff(i,1) = x2(i,1) /
dummy_FE_Hway(i,1);

                            else
```

```
                                City_eff(i,1) = Efficiency(ETW(i),
A(i), B(i), C(i), x1(i,1), density, LHV, T_FTP, S_FTP, X_FTP);
                                Hway_eff(i,1) = Efficiency(ETW(i),
A(i), B(i), C(i), x2(i,1), density, LHV, T_HWFET, S_HWFET, X_HWFET);

                            end

                            break

                        else
                            error = 1;
                        end
                    else
                        error =1;
                    end
                else
                    error =1;
                end
            else
                error =1;
            end
        else
            error =1;
        end
    end

    if error

        City_eff(i,1) = 0;
        Hway_eff(i,1) = 0;
        x1(i,1) = 0;
        x2(i,1) = 0;

    end
end

xlswrite('Data v1.xlsx', {'% City eff'}, num2str(year), 'AN1');
xlswrite('Data v1.xlsx', City_eff, num2str(year), 'AN2');

xlswrite('Data v1.xlsx', {'% Highway eff'}, num2str(year), 'AO1');
xlswrite('Data v1.xlsx', Hway_eff, num2str(year), 'AO2');

xlswrite('Data v1.xlsx', {'UNRND CITY (EPA)'}, num2str(year), 'AP1');
xlswrite('Data v1.xlsx', x1, num2str(year), 'AP2');

xlswrite('Data v1.xlsx', {'UNRND HWY (EPA)'}, num2str(year), 'AQ1');
xlswrite('Data v1.xlsx', x2, num2str(year), 'AQ2');
```

B.1 City FE Calculation MATLAB Sub-Function (EPA 2008 Method)

```
%   City FE Calculation 2008 Method
%   function [City_FE] = City_FE(Bag1, Bag2, Bag3, SC03, US06)

function [City_FE] = City_FE(Bag1, Bag2, Bag3, SC03, US06)

Start_Fuel = 3.6*( (1/Bag1) - (1/Bag3) );
Start_FC = 0.330 * Start_Fuel / 4.1;
Running_FC = 0.82*( (0.48/Bag2) + (0.41/Bag3) + (0.11/US06) ) + 0.1*(
(0.5/Bag2) + (0.5/Bag3) ) + 0.133*1.083*( (1/SC03) - ( (0.61/Bag3) +
(0.39/Bag2)));

City_FE = 0.905 / (Start_FC + Running_FC);
```

B.2 Highway FE Calculation MATLAB Sub-Function (EPA 2008 Method)

```
%   Highway FE Calculation 2008 Method
%   function [Hway_FE] = Hway_FE(Bag1, Bag2, Bag3, SC03, US06, HWFET)

function [Hway_FE] = Hway_FE(Bag1, Bag2, Bag3, SC03, US06, HWFET)

Start_Fuel = 3.6*( (1/Bag1) - (1/Bag3) );
Start_FC = 0.330 * Start_Fuel / 60;
Running_FC = 1.007*( (0.79/US06) + (0.21/HWFET) ) + 0.133*0.377*(
(1/SC03) - ( (0.61/Bag3) + (0.39/Bag2)));

Hway_FE = 0.905 / (Start_FC + Running_FC);
```

Appendix C: Codes of Vehicle Specific Fuel Economy Model

C.1 Main Function

This function takes the input values from the C# GUI that user is specifying the input parameters. Main Function than sends these parameters in desired forms to the main calculation functions.

```
function outdata = mpgCalculate(indata)
%"MPG Calculate" Calculation of mpg through physical approach
%
%   Input parameters:
%        in.disp          - Engine displacement (L)
%        in.cr            - Compression ratio
%        in.maxPower      - Maximum engine power (hp)
%        in.maxRPM        - Engine speed @ maximum power (rpm)
%        in.first         - 1st gear ratio
%        in.second        - 2nd gear ratio
%        in.third         - 3rd gear ratio
%        in.fourth        - 4th gear ratio
%        in.axle          - Axle ratio
%        in.overdrive     - Overdrive ratio
%        in.transfer      - Transfer case ratio
%        in.section       - Section width of the tire (mm)
%        in.aspect        - Aspect ratio of the tire (%)
%        in.rim           - Rim diameter (in)
%        in.A             - Coastdown coefficient A
%        in.B             - Coastdown coefficient B
%        in.C             - Coastdown coefficient C
%
%   Output parameters:
%
%       out.speed         - Speed (mph)
%       out.mpg           - Fuel economy (mpg)
%

% Murat Ates
% (c) The University of Texas at Austin 2008

% Load the data from a structure into individual variable names

   global first second third fourth axle overdrive transfer coefA coefB
coefC;
   global roFuel LHV CV2 combustEff idleRPM;
   global dTire slope constant;
```

```
   global equivalenceRatio compRatio disp fuelAirRatio;

   disp         = indata.disp;
   compRatio    = indata.cr;
   maxPower     = indata.maxPower;
   maxRPM       = indata.maxRPM;
   first        = indata.first;
   second       = indata.second;
   third        = indata.third;
   fourth       = indata.fourth;
   axle         = indata.axle;
   overdrive    = indata.overdrive;
   transfer     = indata.transfer;
   section      = indata.section;
   aspect       = indata.aspect;
   rim          = indata.rim;
   coefA        = indata.A;
   coefB        = indata.B;
   coefC        = indata.C;

%%  Set general properties

    roAir               = 101.21/0.287/293.15;
%   Air density (kg/m^3)
    roFuel              = 744.255;
%   Fuel density (kg/m^3)
    LHV                 = 44.6;
%   Lower heating value (MJ/kg)
    CV2                 = 1609.344*4.448221615*264.1720524/10^6/3600;
    equivalenceRatio    = 1;
%   Equivalence ratio
    AFs                 = 14.6;
%   Standard air-fuel ratio
    FAs                 = 1/AFs;
%   Standard fuel-air ratio

    if equivalenceRatio>1
        combustEff = 1/equivalenceRatio;
%   Combustion efficiency
    elseif equivalenceRatio <= 1
        combustEff = 1.00;
%   Combustion efficiency
    end

    fuelAirRatio        = equivalenceRatio/AFs;
%   Standard fuel air ratio
    x                   = 2;
    idleRPM             = 800;
%   Idle rpm
```

```
% %%  Indicated thermal efficiency coeefficient calculation
% %   eta_ti  = a*N*N + b*N + c where N is rpm
% %   Determine a, b, c coefficients
%
%     dummy_rpm(1,1)  = idleRPM;              % Idle rpm
%     dummy_rpm(2,1)  = 0.5*maxRPM;
%     dummy_rpm(3,1)  = maxRPM;
%
%     eta_ti_MAX  = 0.5*(1-(1/compRatio)^0.4);
%
%     eta_ti(1,1)   = 0.4*eta_ti_MAX;
%     eta_ti(2,1)   = 0.83*eta_ti_MAX;
%     eta_ti(3,1)   = eta_ti_MAX;
%
% % The better your initial condition guess are, the faster
% % the lsqcurvefit command will converge onto a solution
%     initialGuess = [-0.00000001, 0.0001, 0.0223];       %   a, b, c
coefficients
%
% % eta_tiCoeffs is an array containing the optimal values that will
% % generate a curve that will best fit (rpm vs. indicated thermal
efficiency) data
% % Error is the sum of the error squared. The lower this number is,
the better.
%
%     [eta_tiCoeffs] = lsqcurvefit(@indicatedEff, initialGuess,
dummy_rpm, eta_ti);

%%  Tire diameter calculation

    dTire  = (2*section*aspect/2540) + rim;     % Tire diameter (in)

%%  Calculate (indicated thermal efficiency * volumetric efficiency)

    eta_ind_eta_vol  = maxPower*60 /
(combustEff*0.85*roAir*disp*maxRPM*LHV*fuelAirRatio*1.34102209/x);

%% Calculate idle brake power (hp)

    bp_idle  =
eta_ind_eta_vol*0.85*roAir*disp*idleRPM*LHV*fuelAirRatio*1.34102209/120
;

%%  Calculate slope and constant of bp curve

    slope       = (maxPower-bp_idle) / (maxRPM-idleRPM);
    constant    = maxPower - slope*maxRPM;
```

```
%%  Calculate fuel economy

    speed   = [0    0.1 5   10  15  20  25  30  35  40  45  50  55  60
65  70  75  80  85  90  95  100];       % Speed in mph
    mpg(1)  = 0;

    for i=2 : length(speed)
        mpg(i) = calculate(speed(i));
    end

    outdata.speed   = speed;
    outdata.mpg     = mpg;

%% Draw figure

    plot(speed, mpg, 'DisplayName', 'mpg vs speed', 'XDataSource',
'speed', 'YDataSource', 'mpg'); figure(gcf);

    hold on;
    xlabel('Speed (mph)');
    ylabel('Fuel Economy (mpg)');
    title('Fuel Economy vs Speed');
    grid on;
```

C.2 FE CALCULATION FUNCTION

```
%   MPG calculation is done here.
%   Gear Selection and determining transmission and differential
%   efficiencies.
%
%    Transmission efficiencies:
%        1st gear  = 0.85
%        2nd gear  = 0.87
%        3rd gear  = 0.88
%        4th gear  = 0.90


function mpg = calculate(speed)

   global first second third fourth axle overdrive transfer coefA coefB
coefC
   global roFuel LHV CV2 combustEff idleRPM
   global dTire slope constant
```

```
%%   Gear selection setting transmission efficiencies based on
speed(mph)
if speed >= 60
    gear = fourth;
    transEff = 0.90;
else if speed >= 40
        gear = third;
        transEff = 0.88;
    else if speed >= 20
            gear = second;
            transEff = 0.87;
        else
            gear = first;
            transEff = 0.85;
        end
    end
end

%%   Differential Efficiency Calculation
if speed < 150*0.6213711922
    diffEff = 0.6652 + 0.003732*speed*1.609344 -
0.00001061*(speed*1.609344)^2;
else
    diffEff = 0.987;
end

%% Engine RPM calculation

rpm  = speed*gear*axle*overdrive*transfer*63360 / (pi*dTire*60);

%%   If engine speed is less than idle speed of 800 rpm, make it equal
to idle engine speed

if rpm < idleRPM
    rpm = idleRPM;
end

%% LOAD Calculation

bp              = rpm*slope + constant;
%   Brake power produced by engine (hp)
forceRL         = coefA + coefB*speed + coefC*speed^2;
%   Road load force required to move the vehicle in that speed (lbf)
bp_required     =
forceRL*4.448221615*speed*0.44704*0.00134102209/transEff/diffEff;     %
Required brake power to move vehicle in that speed (hp)
load            = bp_required / bp;

%% Mechanical Efficiency Calculation
```

```
if load >= 0.25
    mechanicalEff = 0.85;
else
    mechanicalEff = (0.85/0.25)*load;
end

indicatedThermalEff  = 0.5*indicatedEff(load);
mpg  = 
mechanicalEff*combustEff*indicatedThermalEff*transEff*diffEff*roFuel*LH
V / (3600*CV2*forceRL);
```

C.3 Indicated Thermal Efficiency Calculation Function

```
function indicated = indicatedEff(load)

%
%   Indicated Thermal Efficiency Function
%
%   Air Equivalent Spark Ignition (AESI) Model
%

%%
%
%   Murat Ates
%   (c)2009 The University of Texas at Austin
%
%
%   v1: 5-February-2009
%


%%   Global variables

global compRatio LHV fuelAirRatio combustEff

% compRatio = 9.8;
% LHV                  = 43.6;
% fuelAirRatio         = 1/14.6;
% combustEff = 1;


%%   Determine Friction Power
```

```
% fp = 1.975*10^-5 * sqrt(compRatio) *Stroke*disp*(rpm/100)^2;       %
Eqn 4.18a

%%   Make a guess for f & T1

f   =   0.0285;
T1  =   300;

%%   Constant values

P_ex    =   99;
R_air   =   0.287;

if load == 1
    P1 = P_ex;
else
    P1 = (P_ex-33)*load + 33;
end

h_a_TP  =   airProp(298,'T','h');
h_v_f   =   303.6;
x_e_af  =   0.15;

%%  Set Errors to enter WHILE LOOP at least once

error_f  = 1;
errorT   = 1;

while (error_f >= 0.5) && (errorT >= 0.5)

%   While loop is to optimize temperature and residual fraction

%%  STATE 1

v1 = R_air*T1/P1;
[u1, vr1] = airProp(T1,'T',{'u' 'vr'});

%%   STATE 2

v2 = v1/compRatio;
vr2 = vr1/compRatio;
[T2, u2] = airProp(vr2,'vr',{'T' 'u'});

v3 = v2;

%%   Calculate head added
```

```
q_a_th = combustEff*(1-f)*LHV*1000*fuelAirRatio/(1+fuelAirRatio);

%%   STATE 3

u3 = u2+q_a_th;
[T3, vr3, sT3] = airProp(u3,'u',{'T' 'vr' 'sT'});
P3 = R_air*T3/v3;

%%   STATE 4

vr4 = vr3*compRatio;
[T4, u4] = airProp(vr4,'vr',{'T' 'u'});

%%   STATE 4'

P4p = P_ex;
P5 = P_ex;
P6 = P_ex;
sT4p = sT3 + R_air*log(P4p/P3);
[T4p, h4p] = airProp(sT4p,'sT',{'T' 'h'});
v4p = R_air*T4p/P4p;

%%   STATE 5&6

T5 = T4p;
T6 = T4p;
h5 = h4p;
h6 = h4p;
v5 = v4p;
v6 = v4p;
u6 = airProp(T6,'T','u');

%%   Check initial conditions

f_new = v2/v4p;
h_i = (h_a_TP/(1+fuelAirRatio)) + 0 -
x_e_af*(fuelAirRatio/(1+fuelAirRatio))*h_v_f;   %   Eqn. 4.66c

if load == 1
    h1 = (1-f)*h_i + f*h6;  %   Eqn. 4.60   (NA SI at WOT)
else
    h1 = (1-f)*h_i + f*(u6+P1*v6);  %   Eqn. 4.62 (early IVO)
end
T1new = airProp(h1,'h','T');

error_f = abs(f - f_new)*100/f;
errorT = abs(T1 - T1new)*100/T1;
```

```
%  If new(f & T1) is out of bounds then recalculate by using new values
of
%  f & T1.
f  = f_new;
T1 = T1new;

end


%%   Indicated Thermal Efficiency

w_net = (u1-u2) + (u3-u4) + (P1-P6)*(v1-v2);    %   Eqn. 4.82 (early
IVO)
indicated = w_net/q_a_th;
```

C.4 THERMODYNAMIC PROPERTIES CALCULATION OF IDEAL GAS AIR

```
function varargout=airProp(inputValue,inputName, prop)
%%
% Interpolates thermodynamic properties of AIR as an Ideal Gas
% Temperature range: 250 - 3500 K
%
% Reference:
% Ronald D. Matthews
% Internal Combustion Engines and Automotive Engineering,
% Appendix A1
%
% Values are in SI-units:
%
%   col-#   prop.   units
%   ------------------------
%   1       T       K
%   2       u       kJ/kg
%   3       h       kJ/kg
%   4       sT      kJ/(kgK)
%   5       Pr      -
%   6       vr      -
%
%   inputValue  : This is the value that is going to be used to find
other properties.
%   inputName   : This is the name of the supplied inputValue
%   prop        : prop contains the properties that are requested
%
%
% Example 1:    out=airProp(1000,'h','T')
% Example 2:    [T,u,h,sT,Pr]=airProp(15,'vr',{'T' 'u' 'h' 'sT' 'Pr'})
```

```
% Example 3:    [T,u,h,sT,Pr]=airProp([15 20],'vr',{'T' 'u' 'h' 'sT'
'Pr'})
%
%%
%
% Murat Ates
% (c)2009 The University of Texas at Austin
%
%
% v1:   5-February-2009
%
%%

% check # of input arguments
if ~isequal(nargin,3)
    error('airProp requires 3 input arguments!')
    return
end

% get table
load propTabAir

% find input's column number
inputColumn=find(strcmp(propInfo,inputName));

% if multi property request
if iscell(prop)
    % scan along cells
    for idx=1:length(prop)
        % identify property column
        col=find(strcmp(propInfo,prop(idx)));
        if isempty(col)
            disp(['Property "' char(prop(idx)) '" not recognized!'])
        else
            % create output

varargout{idx}=interp1(airTab(:,inputColumn),airTab(:,col),inputValue);
        end
    end
% single property request
else
    % identify property column
    col=find(strcmp(propInfo,prop));
    if isempty(col)
        disp(['Property "' prop '" not recognized!'])
    else
        % create output
        varargout{1}
=interp1(airTab(:,inputColumn),airTab(:,col),inputValue);
```

```
    end
end
```

C.5 SCRIPT BUILDING MATLAB CODES INTO .NET PLATFORM

```
%%  Build Script
% This script will build the mcode for the TxDOT Vehicle Operating
Costs Project.
%
% This build_mcode makes .NET deployment of MATLAB using Builder for
.NET.
%
%
% Murat Ates
% Copyright 2008 The University of Texas at Austin

%% Determine path names
workdir = pwd();

basedir = fileparts(workdir);
outdir = fullfile(basedir, 'Output');

dnetdir = fullfile(workdir, 'mpgCalculate_dotnet');

%% Determine file names
mfile_mpgCalculate = fullfile(workdir, 'mpgCalculate.m');

dnetdll = fullfile(dnetdir, 'mpgCalculate_dotnet.dll');
dnetctf = fullfile(dnetdir, 'mpgCalculate_dotnet.ctf');

%% Verify mfile can be found
if (exist(mfile_mpgCalculate, 'file') ~= 2)
    error('Unable to find mfile mpgCalculate.m');
end

%% Create directories if needed
if (exist(outdir, 'dir') ~= 7)
    mkdir(outdir);
end

if (exist(dnetdir, 'dir') ~= 7)
    mkdir(dnetdir);
end

%% Build .NET Assembly
disp('Compiling .NET Assembly...');
```

```
eval(['mcc -d ' dnetdir ' -W ''dotnet:mpgCalculate_dotnet,' ...
        'mpgCalculate_dotnet_class,0.0,private'' -T link:lib '
mfile_mpgCalculate]);

% verify assembly was created
if ( (exist(dnetdll, 'file') ~= 2) || ...
     (exist(dnetctf, 'file') ~= 2) )
    error('Failed to successfully compile .NET assembly.');
else
    disp(sprintf('\tDone'));
end

%% Copy .NET Assembly to Output
Copy1 = copyfile(dnetdll, fullfile(outdir, 'mpgCalculate_dotnet.dll'));
Copy2 = copyfile(dnetctf, fullfile(outdir, 'mpgCalculate_dotnet.ctf'));

if ( (Copy1 ~= 1) || (Copy2 ~= 1) )
    error('Unable to copy .NET Assembly to output directory.');
end

%% Clean up
clear Copy1 Copy2 basedir dnetctf dnetdir dnetdll ...
      mfile_mpgCalculate outdir workdir;
```

C.6 C# Graphical User Interface Codes

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;

// MathWorks assemblies that ship with Builder for .NET
// and the MATLAB Component Runtime. These libraries
// should be registered in Global Assembly Cache
using MathWorks.MATLAB.NET.Utility;
using MathWorks.MATLAB.NET.Arrays;

// Assembly built by Builder for .NET containing
// mpgCalculate.m
using mpgCalculate_dotnet;


// Murat Ates
```

```
// Copyright 2008 The University of Texas at Austin
// Texas Vehicle Operating Costs Project

namespace VCost
{
    public partial class MainForm : Form
    {
        public MainForm()
        {
            InitializeComponent();
            //buttonStart.Image =
VCost.Properties.Resources.start_button_75pxl;
            //buttonStart.BackColor = Color.Transparent;

        }

        private void buttonDefaults_Click(object sender, EventArgs e)
        {
            // load default values to input fields
            textBox_disp.Text       = "5.4"     ;
            textBox_cr.Text         = "9.8"     ;
            textBox_maxPower.Text   = "300"     ;
            textBox_maxRPM.Text     = "5000"    ;
            textBox_first.Text      = "2.84"    ;
            textBox_second.Text     = "1.55"    ;
            textBox_third.Text      = "1.00"    ;
            textBox_fourth.Text     = "0.70"    ;
            textBox_axle.Text       = "4.1"     ;
            textBox_overdrive.Text  = "1.0"     ;
            textBox_transfer.Text   = "1.0"     ;
            textBox_section.Text    = "235"     ;
            textBox_aspect.Text     = "70"      ;
            textBox_rim.Text        = "17"      ;
        }

        private void buttonStart_Click(object sender, EventArgs e)
        {
            // check inputs
            if (!checkInputs())
            {
                // Write a warning message and return
                MessageBox.Show("Input Error!" +
                        "\nCheck your inputs!",
                        "VCost Input Error",
                        MessageBoxButtons.OK,
                        MessageBoxIcon.Error);
                return;
            }
```

```
            //  Set coastdown coefficients here explicitly
            //  for the time being. They are going to be changed later.
            string coastdownA, coastdownB, coastdownC;
            coastdownA = "47.7";
            coastdownB = "1.0532";
            coastdownC = "0.03339";


            /*
             * This function calls the mpgCalculate method from
             * inside a .NET assembly created with MATLAB
             * using Builder for .NET
             */

            // Instantiate our .NET class from the MATLAB the MATLAB
created component
            mpgCalculate_dotnet_class FuelEconomyMATLABClass = new
mpgCalculate_dotnet_class();

            // package input into MW Structure Array
            //
            // in this case we are allowing implicit conversion
            // of the system.double into an MWArray which is
            // then used to set the values in field named for the
            // entire MWStructArray. Since we only have one element
            // in our array this is very straightforward.
            String[] InputStructFields = { "disp", "cr", "maxPower",
"maxRPM",
                                            "first", "second",
"third", "fourth",
                                            "axle", "overdrive",
"transfer",
                                            "section", "aspect",
"rim",
                                            "A", "B", "C" };
            MWStructArray Input = new MWStructArray(1, 1,
InputStructFields);
            Input.SetField("disp", Double.Parse(textBox_disp.Text));
            Input.SetField("cr", Double.Parse(textBox_cr.Text));
            Input.SetField("maxPower",
Double.Parse(textBox_maxPower.Text));
            Input.SetField("maxRPM",
Double.Parse(textBox_maxRPM.Text));
            Input.SetField("first", Double.Parse(textBox_first.Text));
            Input.SetField("second",
Double.Parse(textBox_second.Text));
            Input.SetField("third", Double.Parse(textBox_third.Text));
            Input.SetField("fourth",
Double.Parse(textBox_fourth.Text));
```

```
            Input.SetField("axle", Double.Parse(textBox_axle.Text));
            Input.SetField("overdrive",
Double.Parse(textBox_overdrive.Text));
            Input.SetField("transfer",
Double.Parse(textBox_transfer.Text));
            Input.SetField("section",
Double.Parse(textBox_section.Text));
            Input.SetField("aspect",
Double.Parse(textBox_aspect.Text));
            Input.SetField("rim", Double.Parse(textBox_rim.Text));
            Input.SetField("A", Double.Parse(coastdownA));
            Input.SetField("B", Double.Parse(coastdownB));
            Input.SetField("C", Double.Parse(coastdownC));

            //  call mpgCalculate from Assembly specifying the number
            //  of return arguments expected and passing in Input
            MWArray[] Output = FuelEconomyMATLABClass.mpgCalculate(1,
Input);


            //  unpack the output
            string speed, mpg;
            speed =
((MWStructArray)Output[0]).GetField("speed").ToString();
            mpg =
((MWStructArray)Output[0]).GetField("mpg").ToString();

            /*MessageBox.Show("Speed:" +
                        "\n" + speed,
                        "Speed (mph)",
                        MessageBoxButtons.OK,
                        MessageBoxIcon.Information);

            MessageBox.Show("Fuel Economy:" +
                        "\n" + mpg,
                        "Fuel Economy (mpg)",
                        MessageBoxButtons.OK,
                        MessageBoxIcon.Information); */
            //MessageBox.Show("Fuel economy calculation is finished!",
"Result", MessageBoxButtons.OK, MessageBoxIcon.Asterisk);

        }   // end Start Button Click

        private bool checkInputs()
        {
            return (
                (textBox_disp.TextLength > 0) &&
                (textBox_cr.TextLength > 0) &&
                (textBox_maxPower.TextLength > 0) &&
                (textBox_maxRPM.TextLength > 0) &&
```

```
                (textBox_first.TextLength > 0) &&
                (textBox_second.TextLength > 0) &&
                (textBox_third.TextLength > 0) &&
                (textBox_fourth.TextLength > 0) &&
                (textBox_axle.TextLength > 0) &&
                (textBox_overdrive.TextLength > 0) &&
                (textBox_transfer.TextLength > 0) &&
                (textBox_section.TextLength > 0) &&
                (textBox_aspect.TextLength > 0) &&
                (textBox_rim.TextLength > 0)
                );
        }

    }   // end class MainForm
}   // end NameSpace VCost
```

Appendix D: Vehicle Road Test Data Sheet

DATE:

TEST DRIVER:

TEST ENGINEER:

VEHICLE DESCRIPTION: **MUST BE FILLED IN ON DAY OF COASTDOWN TESTS**

MODEL YEAR:		VIN NUMBER:		ENGINE YEAR:	
MAKE:		LICENCE PLATE:		ODOMETER:	miles
MODEL:		CLASS:		TXDOT #	

TIRES*: **MUST BE FILLED IN BEFORE COASTDOWN TESTS AT THE PREPARATION AREA**

SELECT UNITS

psi [ ]

kPa [ ]

TIRE TYPE:

TIRE SIZE:

TIRE MAKE:

PREPARATION AREA TEMPERATURE: °F [ ] °C [ ]

	Manufacturer Specified Tire Pressure	Actual Tire Pressure	TREAD DEPTH > 75%	
Right Front:			YES [ ]	NO [ ]
Right Axle 2 Inside:			YES [ ]	NO [ ]
Right Axle 2 Outside:			YES [ ]	NO [ ]
Right Axle 3 Inside:			YES [ ]	NO [ ]
Right Axle 3 Outside:			YES [ ]	NO [ ]
Right Axle 4 Inside:			YES [ ]	NO [ ]
Right Axle 4 Outside:			YES [ ]	NO [ ]
Right Axle 5 Inside:			YES [ ]	NO [ ]
Right Axle 5 Outside:			YES [ ]	NO [ ]

*** THE TIRES SHOULD HAVE ACCUMULATED A MINIMUM OF 100 MILES AND SHOULD HAVE AT LEAST 75% OF THE ORIGINAL TREAD DEPTH REMAINING, OTHERWISE TEST CANNOT BE STARTED**

TIRES* : MUST BE FILLED IN BEFORE COASTDOWN TESTS AT THE PREPARATION AREA

SELECT UNITS

psi [ ]

kPa [ ]

	Manufacturer Specified Tire Pressure	Actual Tire Pressure	TREAD DEPTH > 75%	
Left Front:			YES [ ]	NO [ ]
Left Axle 2 Inside:			YES [ ]	NO [ ]
Left Axle 2 Outside:			YES [ ]	NO [ ]
Left Axle 3 Inside:			YES [ ]	NO [ ]
Left Axle 3 Outside:			YES [ ]	NO [ ]
Left Axle 4 Inside:			YES [ ]	NO [ ]
Left Axle 4 Outside:			YES [ ]	NO [ ]
Left Axle 5 Inside:			YES [ ]	NO [ ]
Left Axle 5 Outside:			YES [ ]	NO [ ]

* THE TIRES SHOULD HAVE ACCUMULATED A MINIMUM OF 100 MILES AND
SHOULD HAVE AT LEAST 75% OF THE ORIGINAL TREAD DEPTH REMAINING, OTHERWISE TEST CANNOT BE STARTED

FINAL CHECK: MUST BE FILLED IN BEFORE STARTING COASTDOWN TESTS AT THE FIELD

VEHICLE WINDOWS CLOSED* :	YES [ ]	NO [ ]
FOG* :	YES [ ]	NO [ ]
ROAD IS DRY* :	YES [ ]	NO [ ]

* ANSWERS SHOULD BE [YES, NO, YES] RESPECTIVELY, OTHERWISE TEST CANNOT BE STARTED

THE TEST VEHICLE SHOULD HAVE ACCUMULATED A MINIMUM OF 300 MILES PRIOR TO TESTING.
VEHICLE MUST BE DRIVEN A MINIMUM OF 30 MINUTES AT AN AVERAGE OF 50 MPH IMMEDIATELY PRIOR TO TEST.

OTHERWISE TEST CANNOT BE STARTED

AMBIENT TEMPERATURE* & HUMIDITY : MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

°F [ ]

°C [ ]

MINIMUM TEMPERATURE: ______ MAXIMUM TEMPERATURE: ______

AVERAGE TEMPERATURE: ______ = (MIN+MAX) / 2

MINIMUM HUMIDITY: ______ % MAXIMUM HUMIDITY: ______ %

AVERAGE HUMIDITY: ______ % = (MIN+MAX) / 2

* AMBIENT TEMPERATURE SHOULD BE BETWEEN 41 - 90 °F, OTHERWISE THE TEST IS VOID

ATMOSPHERIC PRESSURE: MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

in.Hg [ ]

kPa [ ]

START PRESSURE: ______ FINAL PRESSURE: ______

AVERAGE PRESSURE: ______ =(START+FINAL) / 2

WIND SPEED: MUST BE FILLED IN DURING COASTDOWN TESTS

SELECT UNITS

mph [ ]

km/h [ ]

AVERAGE WIND SPEED: ______ < 10 mph (16 km/h)* DIRECTION: ______ deg

PEAK GUSTS: ______ < 12.2 mph (20 km/h)*

AVERAGE CROSSWIND COMPONENT: ______ < 5 mph (8 km/h)*

* IF THESE VALUES ARE EXCEEDED, THE TEST IS VOID

WHEELS: THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

SIZE: ______ WHEEL COVERS: YES [ ] NO [ ]

ENGINE & DRIVETRAIN SPECIFICATIONS:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

DISPLACEMENT:		COMPRESSION RATIO:	
BORE:		MAX POWER:	
STROKE:		MAX POWER @ rpm:	
# OF CYLINDERS:			

GEAR RATIOS: *	
AXLE RATIOS: *	
TRANSFER CASE RATIO:	
VEHICLE WEIGHT:	
OVERDRIVE RATIO:	

*** STARTING FROM SMALLEST GEAR AND FIRST AXLE**

WEIGHT:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

SELECT UNITS

lbs [ ]

kg [ ]

VEHICLE TEST WEIGHT (DRIVER & INSTRUMENTATION):

TIRE/WHEEL/BRAKE ASSEMBLY: *

Right Front Assembly:		Left Front Assembly:	
Right Axle 2 Assembly:		Left Axle 2 Assembly:	
Right Axle 3 Assembly:		Left Axle 3 Assembly:	
Right Axle 4 Assembly:		Left Axle 4 Assembly:	
Right Axle 5 Assembly:		Left Axle 5 Assembly:	
Right Rear Assembly:		Left Rear Assembly:	

*** WEIGHT OF ALL ROTATING COMPONENTS EXCEPT AXLES**

MISCELLANEOUS:

THIS BOX CAN BE FILLED IN BEFORE OR AFTER THE COASTDOWN TESTS

CHECK VEHICLE SUSPENSION HEIGHTS IF THEY COMPLY WITH THE MANUFACTURER SPECIFICATIONS [ ]

CHECK ENGINE FLUID LEVELS [ ]

TAKE FRONTAL AREA PICTURE [ ]

TEST DATA			
TEST 1:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 2:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 3:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 4:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 5:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 6:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 7:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			

TEST 8:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 9:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 10:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 11:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 12:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 13:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 14:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			

TEST 15:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 16:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 17:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 18:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 19:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			
TEST 20:	FILE NO:	TIME:	DIRECTION:
COMMENTS:			

GENERAL COMMENTS:

COMPLETED BY:	(Printed Name)	(Signature)	(Date)
REVIEWED BY:	(Printed Name)	(Signature)	(Date)
APPROVED BY:	(Printed Name)	(Signature)	(Date)

Appendix E: Coastdown Coefficient Calculation MATLAB Code

```
clear;
clc;

% Read coastdown data
[num, txt] = xlsread('Coastdown Data.xlsx', 'Main');
effectiveMassPounds = num(1,1);     % [lb]
avgWindSpeed = num(2,1);            % [mph]
windDirection = num(3,1);           % [deg]
frontalArea = num(4,1);             % [ft^2]
avgPressure = num(5,1);             % [in.Hg]
avgTemperature = num(6,1);          % [F]
relativeHumidity = num(7,1);        % [%]

theta = windDirection*pi/180;       % Convert degree to radians
wind_X = avgWindSpeed*sin(theta);   % Component of wind parallel to
track [mph]
wind_Y = avgWindSpeed*cos(theta);   % Component of wind perpendicular
to the track [mph]

T0 = 68;    % Standard ambient temperature [deg.F]
P0 = 29;    % Standard ambient pressure [in.Hg]

[num, txt] = xlsread('Coastdown Data.xlsx', 'Data'); %[num] includes
all Time [seconds] vs. Speed [mph] data
[row, col] = size(num);


for i=1 : (col/2)

    indice = find(isfinite(num(:,2*i-1)), 1, 'last' );      %
Correction to compensate different row sizes. At num matrice MATLAB
puts NaN for shorter columns.

    [f0(i,1), f2(i,1), RMSE(i,1)]= curveFitting (num(1:indice,2*i-1),
num(1:indice,2*i), effectiveMassPounds);
    testName(i,1) = txt(1, 2*i-1);
end

% Data Acceptability Criteria #1
[testName_1, f0_1, f2_1, RMSE_1, checkResult]= criteria1 (testName, f0,
f2, RMSE);

if (checkResult == 0)
    msgbox('INVALID TEST: Criteria #1','Error','error')
```

```
    return
end

% Data Acceptability Criteria 2a
[testName_2a, f0_2a, f2_2a, RMSE_2a, checkResult]= criteria2a
(testName_1, f0_1, f2_1, RMSE_1);

if (checkResult == 0)
    msgbox('INVALID TEST: Criteria #2a','Error','error')
    return
end

% Data Acceptability Criteria 2b
[testName_2b, f0_2b, f2_2b, RMSE_2b, checkResult]= criteria2a
(testName_2a, f0_2a, f2_2a, RMSE_2a);

if (checkResult == 0)
    msgbox('INVALID TEST: Criteria #2b','Error','error')
    return
end

% Average f0's and f2's of all remaining runs to determine an fo and
f2.
f0Accepted = mean(f0_2b);
f2Accepted = mean(f2_2b);


% Data Correction
% The average f0 and f2 values must now be corrected to a standard set
of
% ambient constions. The standard constions are:
%        a. Temperature - 20 deg.C (68 deg.F)
%        b. Atmospheric pressure - 736.6 mm Hg (29.00 in.Hg)
%        c. Zero wind
%        d. The effect of humidity on air density may be ignored


% AIR_DENSITY calculates density of air
%  Usage :[ro] = air_density(t,hr,p)
%  Inputs:    t = ambient temperature (ºC)
%            hr = relative humidity [%]
%             p = ambient pressure [Pa]  (1000 mb = 1e5 Pa)
%  Output:   ro = air density [kg/m3]
airDensity = air_density((avgTemperature-32)/1.8, relativeHumidity,
avgPressure*3386.388158);       % [kg/m^3]


% SAE J1263 Equation 12
```

```
% Wind correction to f0

muPrime = 50*10^-6;     % Velocity coefficient of rolling resistance
[1/mph^2]
C_DY = 3.4;             % Crosswind aerodynamic drag coefficient
[(ft/s)^2/mph^2]

rollingResistance = (f0Accepted - f2Accepted*wind_X^2 -
(0.5*airDensity*C_DY*frontalArea*wind_Y^2)*(1.94*10^-3)) / (1 -
muPrime*wind_X^2);

% SAE J1263 Equation 14
% Temperature correction to f0

k_t = 4.8*10^-3;        % Temperature coefficient of rolling ressitance
[1/deg.F]

f0Prime = rollingResistance*(1 + k_t*(avgTemperature - T0));

% SAE J1263 Equation 16
% Air density correction to f2

f2Prime = (P0*(avgTemperature + 459.67)/avgPressure/(T0 + 459.67)) *
(f2Accepted - muPrime*rollingResistance) + muPrime*f0Prime;
```

E.1 MODEL EQUATION

```
function speed = modelEquation (initialGuess, time)
f0 = initialGuess(1);
f2 = initialGuess(2);

conversionFactor = 0.682; % time [seconds], effectiveMass [slugs]
global initialSpeed effectiveMass

% Equation 7 which is our model to represent the data from SAE J1263
speed = sqrt(f0/f2) * tan( atan( sqrt(f2/f0)*initialSpeed ) -
sqrt(f0*f2)*time*conversionFactor/effectiveMass );
```

E.2 DATA ACCEPTABILITY CRITERIA 1

```
% Data Acceptability Criteria #1
%
%
% If the Root Mean Square Error (RMSE) exceeds 0.25 mph on any
individual
```

```
% run, discard that run and the paired run in the opposite direction.
If
% less than three pairs comply with this criterion, the test run is
% invalid.

function  [testName, f0, f2, RMSE, checkResult]= criteria1 (testName,
f0, f2, RMSE)

locator = find(RMSE>5);    % Changed from 0.25 to 5

[row, col] = size(RMSE);
for i=1 : row
    Result(i,1) = cellstr('OK');
end

if isempty(locator)
    checkResult = 1;
    return
else
    [row,col] = size(locator);
    for i=1 : row
        if mod(locator(i),2)    % When it is an odd number delete that
row and the consequitive one
            Result(locator(i),1) = cellstr('delete');
            Result(locator(i)+1,1) = cellstr('delete');
        else
            Result(locator(i),1) = cellstr('delete');
            Result(locator(i)-1,1) = cellstr('delete');
        end
    end

    for i=1 : (2*length(locator))
        for j=1 : length(RMSE)
            if strcmp(Result(j) ,'delete') == 1
                RMSE(j) = [];
                f0(j) = [];
                f2(j) = [];
                testName(j) = [];
                Result(j) = [];
            break
            end
        end

    if length(RMSE) < 6
        checkResult = 0;
        return
    end

    end
```

```
end


[row, col] = size(RMSE);

if (row >= 6)
    checkResult = 1;    % If less than 3 pairs comply with this
criteria then [checkResult = 0], otherwise [checkResult = 1]
else
    checkResult = 0;
end
```

E.3 Data Acceptability Criteria 2a

```
function [testName, f0, f2, RMSE, checkResult]= criteria2a (testName,
f0, f2, RMSE)

if ( std(f0) < 2.5 || std(f0) < mean(f0)*0.5 )     % Changed from 0.05
to 0.5
    checkResult = 1;
    return
else

    while ( std(f0) >= 2.5 && std(f0) >= mean(f0)*0.2 )      % Changed
from 0.05 to 0.2
        [maxValue, row] = max(abs(f0-mean(f0)));
        if mod(row,2)
            RMSE(row) = [];
            RMSE(row) = [];

            f0(row) = [];
            f0(row) = [];

            f2(row) = [];
            f2(row) = [];

            testName(row) = [];
            testName(row) = [];
        else
            RMSE(row) = [];
            RMSE(row-1) = [];

            f0(row) = [];
            f0(row-1) = [];

            f2(row) = [];
```

```
            f2(row-1) = [];

            testName(row) = [];
            testName(row-1) = [];
        end

    if length(RMSE) < 6
        checkResult = 0;
        return
    end

    end

end

[row, col] = size(RMSE);

if (row >= 6)
    checkResult = 1;    % If less than 3 pairs comply with this
criteria then [checkResult = 0], otherwise [checkResult = 1]
else
    checkResult = 0;
end
```

E.4 DATA ACCEPTABILITY CRITERIA 2B

```
function [testName, f0, f2, RMSE, checkResult]= criteria2b (testName,
f0, f2, RMSE)

if ( std(f2) < 0.001 || std(f2) < mean(f2)*0.03 )
    checkResult = 1;
    return
else

    while ( std(f2) >= 0.001 && std(f2) >= mean(f2)*0.03 )
        [maxValue, row] = max(abs(f2-mean(f2)));
        if mod(row,2)
            RMSE(row) = [];
            RMSE(row) = [];

            f0(row) = [];
            f0(row) = [];

            f2(row) = [];
            f2(row) = [];
```

```
            testName(row) = [];
            testName(row) = [];
        else
            RMSE(row) = [];
            RMSE(row-1) = [];

            f0(row) = [];
            f0(row-1) = [];

            f2(row) = [];
            f2(row-1) = [];

            testName(row) = [];
            testName(row-1) = [];
        end

    if length(RMSE) < 6
        checkResult = 0;
        return
    end

    end

end

[row, col] = size(RMSE);

if (row >= 6)
    checkResult = 1;    % If less than 3 pairs comply with this
criteria then [checkResult = 0], otherwise [checkResult = 1]
else
    checkResult = 0;
end
```

E.5 AIR DENSITY CALCULATION

```
function [ro] = air_density(t,hr,p)
% AIR_DENSITY calculates density of air
%  Usage :[ro] = air_density(t,hr,p)
%  Inputs:   t = ambient temperature (ºC)
%           hr = relative humidity [%]
%            p = ambient pressure [Pa]  (1000 mb = 1e5 Pa)
%  Output:  ro = air density [kg/m3]

%
%  Refs:
```

```
% 1)'Equation for the Determination of the Density of Moist Air' P.
Giacomo  Metrologia 18, 33-40 (1982)
% 2)'Equation for the Determination of the Density of Moist Air' R. S.
Davis Metrologia 29, 67-70 (1992)
%
% ver 1.0   06/10/2006    Jose Luis Prego Borges (Sensor & System
Group, Universitat Politecnica de Catalunya)
% ver 1.1   05-Feb-2007   Richard Signell (rsignell@usgs.gov)
Vectorized

%-----------------------------------------------------------------------
---
T0 = 273.16;         % Triple point of water (aprox. 0ºC)
 T = T0 + t;         % Ambient temperature in ºKelvin

%-----------------------------------------------------------------------
---
%-----------------------------------------------------------------------
---
% 1) Coefficients values

 R =  8.314510;           % Molar ideal gas constant   [J/(mol.ºK)]
Mv = 18.015*10^-3;        % Molar mass of water vapour [kg/mol]
Ma = 28.9635*10^-3;       % Molar mass of dry air      [kg/mol]

 A =  1.2378847*10^-5;    % [ºK^-2]
 B = -1.9121316*10^-2;    % [ºK^-1]
 C = 33.93711047;         %
 D = -6.3431645*10^3;     % [ºK]

a0 =  1.58123*10^-6;      % [ºK/Pa]
a1 = -2.9331*10^-8;       % [1/Pa]
a2 =  1.1043*10^-10;      % [1/(ºK.Pa)]
b0 =  5.707*10^-6;        % [ºK/Pa]
b1 = -2.051*10^-8;        % [1/Pa]
c0 =  1.9898*10^-4;       % [ºK/Pa]
c1 = -2.376*10^-6;        % [1/Pa]
 d =  1.83*10^-11;        % [ºK^2/Pa^2]
 e = -0.765*10^-8;        % [ºK^2/Pa^2]

%-----------------------------------------------------------------------
---
% 2) Calculation of the saturation vapour pressure at ambient
temperature, in [Pa]
psv = exp(A.*(T.^2) + B.*T + C + D./T);   % [Pa]


%-----------------------------------------------------------------------
---
```

```
% 3) Calculation of the enhancement factor at ambient temperature and
pressure
fpt = 1.00062 + (3.14*10^-8)*p + (5.6*10^-7)*(t.^2);


%-----------------------------------------------------------------------
---
% 4) Calculation of the mole fraction of water vapour
 xv = hr.*fpt.*psv.*(1./p)*(10^-2);


%-----------------------------------------------------------------------
---
% 5) Calculation of the compressibility factor of air
  Z = 1 - ((p./T).*(a0 + a1*t + a2*(t.^2) + (b0+b1*t).*xv +
(c0+c1*t).*(xv.^2))) + ((p.^2/T.^2).*(d + e.*(xv.^2)));


%-----------------------------------------------------------------------
---
% 6) Final calculation of the air density in [kg/m^3]
 ro = (p.*Ma./(Z.*R.*T)).*(1 - xv.*(1-Mv./Ma));
```

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Vita

Murat Ates was born in Antalya, Turkey on February 15, 1982, the son of Abdullah and Zeynep Ates. After the primary school he got through the Anatolian High School Exam and entered to Metin-Nuran Cakallikli Anatolian High School where education language is English. In 2001 he entered to Middle East Technical University (METU), Mechanical Engineering Department by being in top 1% in the Turkish University Entrance Exam. He graduated with honor roll from METU in 2006 by receiving his Bachelor of Science degree and in the same year he was admitted to the University of Texas at Austin, Mechanical Engineering Department as a Master's student.

He received a five years scholarship from one of Turkey's biggest company Sabanci Holding during his undergraduate studies. Moreover he completed internships at Fiat-GM Powertrain and Procter & Gamble, which gave him opportunity to work in a global diverse environment.

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